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ASSESSMENT OF NO_x EMISSION FACTORS FOR DIRECT-FIRED HEATERS

by

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16. ABSTRACT The report gives results of a review of available data on emission factors for major categories of direct-fired heaters. Systematic studies were analyzed to develop emission factors for oxides of nitrogen (NOx) at various levels of combustion air preheat used in major energy-consuming industries. Industrial fuel use in non-boiler applications amounted to about 60% of total industrial fuel consumption in 1980. Historically, air pollution control of these sources has focused on emissions of NOx. NOx, however, currently are felt to play a role in the formation of acid precipitation. The increasing use and potential for use of preheated combustion air for energy conservation may result in increased emissions of NOx from direct-fired process heaters. Limited data show that NOx emission rates rise as combustion air temperature increases. Studies indicate that a significant market for high temperature heat recovery equipment for use with many types of industrial sources will exist as they become proven and are applied to both new and existing sources. If these devices, which can preheat combustion air to 1093-plus C, are applied extensively, nationwide emissions of NOx could increase significantly.

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Nitrogen Oxides	Combustion	Stationary Sources	07B	21B
Heating Equipment	Processing	Preheaters	13A	13H
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ABSTRACT

Industrial fuel use in non-boiler applications amounted to approximately 60 percent of total industrial fuel consumption in 1980. Historically, air pollution control of these sources has focused on emissions of particulates and sulfur compounds with much less emphasis on emissions of oxides of nitrogen. Nitrogen oxides, however, currently are felt to play a role in the formation of acid precipitation.

The increasing use and potential for use of preheated combustion air for energy conservation may result in increased emissions of oxides of nitrogen from direct-fired process heaters. Limited data show that nitrogen oxides emission rates rise as combustion air temperature increases. Studies indicate that a significant market for high temperature heat recovery equipment for use with many types of industrial sources will exist as they become proven and are applied to both new and existing sources. If these devices, which can preheat combustion air up to 2000°F and beyond, are applied extensively, nationwide emissions of oxides of nitrogen could increase significantly.

Under this work assignment, available data on emission factors for major categories of direct-fired heaters were reviewed. Systematic studies performed by the Institute of Gas Technology under contract to the Gas Research Institute and Southern California Gas Company were analyzed to develop emission factors for oxides of nitrogen at various levels of combustion air preheat used in major energy-consuming industries. Table 1-1 gives the results of this analysis.

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SECTION 1
SUMMARY

INTRODUCTION

Industrial fuel use in non-boiler applications amounted to approximately 60 percent of total industrial fuel consumption in 1980. Historically, air pollution control of these sources has focused on emissions of particulate matter and sulfur compounds with much less emphasis on emissions of oxides of nitrogen. Nitrogen oxides, however, currently are felt to play a role in the formation of acid precipitation.

The increasing use and potential for use of preheated combustion air for energy conservation may result in increased emissions of oxides of nitrogen from direct-fired process heaters. Limited data show that nitrogen oxides emission rates rise as combustion air temperature increases. Studies indicate that a significant market for high-temperature heat recovery equipment for use with many types of industrial sources will exist as they become proven and are applied to both new and existing sources. If these devices, which can preheat combustion air up to 2000°F and beyond, are applied extensively, nationwide emissions of oxides of nitrogen could increase significantly.

The objective of this report is to provide technical information on NO_x emissions attributable to energy-intensive direct-fired process heaters. Specific tasks undertaken to quantify current NO_x emissions and trends in NO_x resulting from technology changes were as follows:

- Define energy-intensive direct-fired process heaters.
- Describe the fundamentals of NO_x formation.
- Investigate technology changes leading to energy conservation.
- Determine the effect of energy conservation techniques, primarily combustion air preheat, on NO_x emissions.
- Develop NO_x emission factors for direct-fired process heaters employing various levels of combustion air preheat.

ENERGY-INTENSIVE HEATERS

Several energy-intensive industrial processes were identified as capable of producing and using high-temperature preheated combustion air. These are (1) steel reheat furnaces; (2) steel soaking pits; (3) aluminum reheat furnaces; (4) aluminum melting furnaces; (5) steel forging furnaces; (6) annealing furnaces; (7) titanium melting furnaces; (8) nickel melting furnaces; (9) cement kilns; and (10) glass melting furnaces. Although preheated combustion air presents opportunities for energy savings in these industrial process heaters, it also has the drawback that increased combustion air temperatures lead to increases in thermal NO_x emitted from these stationary sources. NO_x emissions could increase from an estimated 6.73 million tons in 1980 to an estimated 8.31 million tons in 1990 due in part to combustion air preheat.

FUNDAMENTALS OF NO_x FORMATION

Regardless of the type of combustion device, oxides of nitrogen are formed in combustion processes by the thermal fixation of atmospheric nitrogen and by the conversion of fuel-bound nitrogen. Total NO_x emissions and the contribution of each mechanism to the total depend upon the heater design, heater operating conditions, and the type of fuel burned.

Combustion generates high temperatures that result in molecular dissociation of the oxygen in the combustion air. The separate oxygen atoms react with many other atoms in the combustion reactions, but some react with the otherwise stable N_2 molecule to form NO.

Through the use of thermodynamic and chemical kinetic analyses, it is possible to model approximately the controlling influences of combustion stoichiometry, temperature, and residence time, assuming one-dimensional homogeneous air/fuel flow. Explicitly, the theoretical model shows that the rate of formation of NO is sensitive to the mole fractions of oxygen and nitrogen. Also, the model predicts the extreme sensitivity of NO formation to temperature. As the temperature increases, the rate constants increase in an exponential fashion. Since preheat of combustion air can increase the peak flame temperature in the combustion zone, air preheat can increase thermal NO formation.

On practical equipment, combustion fundamentals of thermal NO formation include mixing, turbulence, heat transfer, and composition along with temperature within the combustion zone. Thus, a quantitative determination of thermal NO formation at various levels of combustion air preheat must be based on specific furnace designs and operating parameters.

In general, all fuel-bound nitrogen can be assumed to be converted rapidly to NO. As with thermal NO formation, the conversion of fuel nitrogen depends on combustion conditions. This dependency, however, has been found to be less sensitive to design and operating parameters. For this analysis, it is assumed that all fuel-bound nitrogen is converted to NO with no affect by combustion air temperature.

PROCESS HEATER DESIGN AND OPERATION

The primary function of process heater systems is to provide controlled efficient conversion of the chemical energy of fuel into an energy form that can be transferred as heat to process fluids. Process heaters do this by introducing the fuel and air for combustion, mixing these reactants, igniting the mixture, and distributing the flame envelope and the products of combustion. A process heater should function so that the fuel and air input is ignited and burned continuously and immediately upon its entry into the furnace. The total fuel burning system required to do this consists of subsystems for air handling, fuel handling, ignition, and combustion product removal plus the burners and the furnace. Assuming the burners are chosen properly in furnace system designs, trends in formation of oxides of nitrogen can be evaluated for many various types of furnaces by analysis of a few basic burner types.

As industries seek ways of reducing operating costs by fuel conversion, adjustment of operating parameters for optimum fuel conservation may be performed. Optimization of fuel use using heat recovery techniques, however, may lead to increases in pollutant emissions. Currently, one of the more prevalent heat recovery techniques involves preheating combustion air to achieve greater furnace efficiency. This air preheat also increases NO_x formation by increasing the temperature in the combustion zone. A systematic study of energy-intensive industries reveals two broad, distinct classifications of industrial processes capable of using preheated combustion air. The

steel, aluminum, and other metal processing industries and petroleum refining industries use baffle burners capable of using air preheat in the range of 800-1200°F. Furnaces common in the glass manufacturing and cement manufacturing industries can use preheated combustion air in the range of 1600-2200°F.

Several major companies are involved in the manufacture of burners capable of accepting high temperature combustion air. In order to evaluate the effect of combustion air preheat on NO_x emissions from direct-fired process heaters, burners must be selected as representative of the burners that are used or potentially could be used for the specific furnaces under consideration. Steel reheating processes, steel soaking processes, and aluminum melting processes can be represented by the Bloom hot air baffle burner based on its extent of use in these processes currently. Because of process similarity and furnace design and operation, the Bloom hot air baffle burner would be representative of the nickel and titanium melting furnaces also. The Bloom burner also is used in refinery process heaters. The North American refractory-lined burner is used in the glass industry, and because of similar process heat requirements, it also may be considered as representative of burners used in cement kilns. Thus, by analysis of the various operating conditions of two burners, the effect of combustion air preheat on NO_x emissions from energy-intensive processes can be estimated.

EFFECT OF HEATER OPERATION ON NO_x EMISSIONS

Emission factors for NO_x at various levels of combustion air preheat for two furnaces representing the broad classifications of direct-fired heaters used in energy-intensive industries, for a theoretically-based model furnace, and for prototype low-NO_x burners capable of industrial use have been developed. Systematic studies performed by the Institute of Gas Technology under contract to the Gas Research Institute and Southern California Gas Company provided the basis for development of these emission factors. These results were used to develop NO_x emission factors for the range of process heaters used in energy-intensive industries at various levels of combustion air preheat. Table 1-1 gives the results of this analysis.

TABLE 1-1. Emission Factor Summary*

Furnace	Fuel	NO_x Emission Factors (lbs $NO_2/10^6$ Btu) Preheat Temperature (°F)			
		800	1200	1600	2000
Steel Reheat	Coke Oven Gas	0.34	.72	1.40	3.20
	Natural Gas	0.34	0.72	1.40	3.20
Steel Soaking Pit	Coke Oven Gas	0.34	0.72	1.40	3.20
	Natural Gas	0.34	0.72	1.40	3.20
Aluminum Reheat	Residual Fuel Oil	0.64	1.02	1.70	3.50
	Natural Gas	0.34	0.72	1.40	3.20
Aluminum Melting	Residual Fuel Oil	0.64	1.02	1.70	3.50
	Natural Gas	0.34	0.72	1.40	3.20
Steel Forging	Natural Gas	0.34	0.72	1.40	3.20
Annealing	Natural Gas	0.34	0.72	1.40	3.20
Titanium Melting	Natural Gas	0.34	0.72	1.40	3.20
Nickel Melting	Natural Gas	0.34	0.72	1.40	3.20
Cement Kiln	Natural Gas	--	--	0.80	1.80
Glass Melting	Natural Gas	--	--	0.80	1.80
Refinery Process	Natural Gas	0.34	0.72	1.40	3.20

*These emission factors are adequate for use in emission inventory preparation. Application of these factors to specific heaters are subject to the following limitations:

i) The emission factors are based on experimental data only from two types of industrial furnaces, and they are suggested for application to other industrial furnaces based on similarities in furnace design and operating conditions,

ii) Except for the glass melting furnace and cement kiln, the emission factors for 1600 and 2,000°F air preheat temperatures are extrapolated values:

iii) For residual fuel oil, the listed NO_x emission factors are for 0.3 weight percent N content and 19,600 Btu/lb heating value, assuming 100 percent conversion of fuel N to NO.

SECTION 2
INTRODUCTION

PROJECT OBJECTIVES

This analysis is part of an extensive project to estimate environmental consequences of industrial energy use and conservation. Emission factors developed in this study will serve as inputs to an analytical model that simulates technology choices and makes projections of future energy and associated nitrogen oxides (NO_x) emissions by industry. The model, developed by Energy and Environmental Analysis, Inc. (EEA), is based on the premise that technology choices are made to minimize the cost of production. In some cases, low cost energy technology may lead to increases in NO_x emissions.

Historically, air pollution control of sources of industrial fuel use has been focused on emissions of particulate matter and sulfur compounds. NO_x emitted from industrial fuel combustion, however, is believed to play a role in the formation of acid precipitation. Thus, knowledge of the significance and control effectiveness of these NO_x emissions and their relationship to energy conservation is necessary to evaluate the current and future effects of industrial fuel combustion on acid precipitation.

The objective of this analysis is to provide technical information on NO_x emissions attributable to energy-intensive direct-fired process heaters. Specific analyses necessary to quantify current NO_x emissions and trends in NO_x emissions resulting from technology changes are as follows:

- Define energy-intensive direct-fired process heaters.
- Investigate technology changes leading to energy conservation.
- Determine effect of energy conservation techniques on NO_x emissions.
- Develop NO_x emission factors for direct-fired process heaters using energy conservation techniques.

BACKGROUND

The industrial sector is the most heterogeneous and complex energy consumptive activity and is responsible for 40 percent of total domestic energy consumption. Manufacturing is the most energy-intensive activity within the industrial sector. Manufacturing consumes 24 quads/year of energy, which accounts for over 80 percent of the industrial sector's energy consumption. The manufacturing activity is composed of 20 2-digit Standard Industrial Classification groups. Six of these groups (food, paper, chemicals, petroleum and coal, mineral processing, and primary metals) account for over 80 percent of the manufacturing activity's annual energy consumption.[1]

The fuels consumed in the manufacturing portion of the industrial sector are used in five basic ways: (1) to generate on-site electricity; (2) to provide direct-fired process heat; (3) to produce process and space heating steam in industrial boilers; (4) to provide chemical feedstocks; and (5) to provide a reducing agent in metallurgical processing. Direct-fired heat accounts for approximately 40 percent of the fuel use. Table 2-1 shows the direct-fired fuel uses of each of the six industry groups.[2]

Direct-tired processes are those that burn fossil fuels to supply thermal energy from the flame or from products of combustion. Whenever fossil fuels are burned in enclosed combustion devices, NO_x emissions are formed by the thermal fixation of atmospheric nitrogen and by the conversion of fuel-bound nitrogen. The amount of NO_x formed is influenced by the combustion device design and the operating conditions; these factors also influence the efficiency of fuel use.

Industrial direct-firing takes place in various types of equipment. These types include specifically engineered process equipment and "off-the-shelf" equipment. The types of equipment used in direct-fired processes and estimates of energy consumptions associated with these equipment types are presented in Table 2-2.[2] Each of the devices listed in Table 2-2 is designed and operated in such a manner as to accomplish the heat transfer for a particular process.

With increasing energy demands and the need for conservation and efficient use of energy, utilization of hot process exhaust gases to preheat combustion air has become an attractive means to conserve energy. Until recently there

TABLE 2-1. Direct-Fired Fuel Uses of Major Industrial Groups. (1972)

Industry Group	Direct-Fired Fuel Use (10^{12} Btu/year)
Food	45.9
Paper	51.1
Chemicals	1538.4
Petroleum	1943.6
Stone, Clay, Glass	1051.7
Primary Metals	1493.0
Other	794.2
Total	6917.9

TABLE 2-2. Direct-Fired Process Equipment

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
Food/20	Lime kiln	CO_2 production	Beet sugar	3.25
	Char kiln	Charring	Cane sugar refining	0.69
	Kiln	Barley heating and drying	Malt	8.11
	Afterburner	Firing of unburned fuel	Meat packing	1.50
	Afterburner	Firing of unburned fuel	Sausages, prepared meats	0.70
	Data not available (DNA)	Barrel charring	Distilled spirits	0.08
	Dryer	Drying	Prepared feeds	23.07
	Dryer	Drying	Soybean oil	9.16
	Drying kiln	Drying	Milk	2.43
	Drying furnace	Drying	Beet sugar	21.78
	Dryer furnace	Drying	Wet corn milling	9.64
	Drying oven	Drying	Cereal	2.50
	Oven	Smoking/cooking	Meat packing	2.25
	Oven	Baking	Baked goods	18.04
	Oven	Baking	Cookies, crackers	7.71
	Oven/smokehouse	Cooking/smoking	Sausage, prepared meats	1.04
	Fryer	Frying	Baked goods	1.20
	Hot water heater	Water heating	Baked goods	2.41
	Hot water heater	Water heating	Animal, marine fats	0.33
	Hot water heater	Water heating	Poultry dressing	0.11
	Hot water heater	Water heating	Ice	0.31
	Cooker	Cooking	Sausage, prepared meats	0.12
	Gas singer	Hair removal	Meat packing	1.50
	Dryers, various	Drying	Flour, grain	2.90
	Dryers, various	Drying	Malt beverages	2.03
	Dryers, various	Drying	Cheese	6.28
	Dryers, various	Drying	Condensed, evaporated milk	5.29
	Dryers, various	Drying	Coffee	1.26
	Dryers, various	Drying	Butter	2.47
	Dryers, various	Drying	Rice milling	0.81
	Dryers, various	Drying	Ice cream	0.03
	Dryers, various	Pomace drying	Wines	0.16
	Can washer	Can washing	Soft drinks	0.90
	Roasters, various	Roasting	Confections	3.10
	Roasters, various	Roasting	Coffee	2.21
	Roasters, various	Roasting	Chocolate	1.54
	DNA	Cooking	Confections	1.96
	Evaporators	Evaporation, dehydration	Flavoring extracts	6.14
Paper/26	Rotary lime kiln	White liquor production	Pulp	12.87
	Gas-fired infra-red burner	Drying	Coated paper	26.88

(Continued)

TABLE 2-2. (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
Chemicals/28	Tubular preheater	Naphtha cracking	Ethylene/propylene	194.46
	Tubular preheater	Naphtha cracking	Butadiene	3.39
	Tubular preheater	Veba Chemic	Ethanol	1.67
	Tubular preheater	Shell Sulfolane	Benzene	44.83
	Tubular preheater	Dynamit Nobel	Dimethyl terephthalate	3.90
	Oil furnace	Furnace black	Carbon black	35.71
	Fired steam superheater	Monsanto	Ethylbenzene/styrene	19.84
	Tubular furnace	Steam-hydrocarbon reforming	Ammonia	139.00
	Kiln (rotary)	Ore nodulizing	Phosphorus	2.54
	Kiln (rotary)	Drying, calcination	Uranium oxide	1.45
	Kiln (rotary)	Calcination	Lithium hydroxide	2.62
	Kiln (rotary)	Ore roasting	Mercury	0.02
	Dryer (rotary)	Concentrate drying	Phosphoric acid	6.81
	Dryer (rotary)	Drying	Carbon black	3.97
	Dryer (rotary)	Potash drying	Potash	2.23
	Dryer (rotary)	Borax drying	Borax	0.40
	Dryer (rotary)	Drying	Synthetic rubber-butyl	0.01
	Dryer (spray)	Drying	PVC and copolymers	6.90
	Dryer (tray)	Borax drying	Borax	0.39
	Dryer	Drying	Barite	0.16
	Dryer	Drying, calcination	Rare earths	0.13
	Autoclave	Leaching	Uranium oxide	1.15
	Catalytic combustion furnace	O_2 burnout (purification)	Argon	0.04
	Roaster	Precipitate roasting	Arsenic oxide	0.12
	Roaster (multiple hearth)	Ore roasting	Mercury	0.02
	Retort furnace	Ore roasting	Mercury	0.02
	DNA	Leaching	Potash	2.14
	DNA	Granulating	Potash	1.06
	Various	DSM low sulfate	Caprolactam	0.21
	Various	Continuous mass polymerization	Polystyrene and copolymers	2.56
	Various	ICI low pressure	Methanol	16.63
Petroleum/29	Tubular preheater	Atmospheric distillation	Oil and gas	529.30
	Tubular preheater	Vacuum distillation	Oil and gas	296.50
	Tubular preheater	Thermal cracking	Oil and gas	23.40

(Continued)

TABLE 2-2. (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Tubular preheater	Fluid catalytic cracking	Oil and gas	229.20
	Tubular preheater	Catalytic reforming	Oil and gas	407.10
	Tubular preheater	Naphtha hydrotreating	Oil and gas	77.80
	Tubular preheater	Gas oil hydrotreating	Oil and gas	119.90
	Visbreaking furnace	Visbreaking	Oil and gas	17.90
	Refinery delayed coking unit	Delayed coking	Oil and gas	266.20
	Reboiler furnace	Alkylation	Oil and gas	42.80
Stone/Clay/ Glass/Concrete/ 32	Kiln (rotary)	Clinker burning	Cement	324.50
	Kiln (rotary)	Calcination	Lime	116.68
	Kiln (rotary)	Calcination	Gypsum	3.91
	Kiln (rotary)	Calcination	Diatomite	1.07
	Kiln (vertical shaft)	Calcination	Lime	29.17
	Kiln (tunnel)	Drying, firing	Brick	34.34
	Kiln (tunnel)	Drying, firing	Fireclay brick	3.34
	Kiln (tunnel)	Curing, drying, firing	Basic brick	0.82
	Kiln (periodic)	Drying, firing	Brick	15.49
	Kiln (periodic)	Drying, firing	Fireclay brick	3.34
	Kiln (periodic)	Curing, drying, firing	Basic brick	0.82
	Kiln (gypsum pot)	Calcination	Gypsum	3.91
	Reverberatory furnace	Melting, firing, conditioning	Glass	227.18
	Lehr (tunnel oven)	Annealing	Glass	25.57
	Impregnation unit	Pitch impregnation	Basic brick	0.05
	Hammer mill-hot blower	Drying	Diatomite	2.22
	Furnace (stationary, vertical)	Heat expansion	Perlite	0.82
	Furnace (vertical)	Exfoliation	Vermiculite	0.48
	Furnace (stationary, horizontal)	Heat expansion	Perlite	0.82
	Furnace (rotary, horizontal)	Heat expansion	Perlite	0.82
	DNA	Forming	Glass	5.77
	Dryer (rotary)	Drying	Clays	19.68
	Dryer (rotary)	Drying	Gypsum	1.35
	Dryer (rotary)	Drying	Pumice	0.81
	Dryer (rotary)	Drying	Mica (ground)	0.58
	Dryer (rotary)	Drying	Feldspar	0.52
	Dryer (rotary)	Drying	Talc and soapstone	0.02
	Dryer (tunnel)	Drying	Basic brick	0.82
	Dryer (flash)	Drying	Talc and soapstone	0.02

(Continued)

TABLE 2-2. (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Dryer (vertical)	Drying	Asbestos	0.17
	Dryer	Drying	Graphite	0.08
	Heater	Pitch heating	Basic brick	0.84
Metals/33	Pellet furnace (shaft, traveling grate, rotary kiln, grate-kiln)	Pelletizing	Iron and steel	26.45
	Traveling grate furnace	Sintering	Lead	0.55
	Sintering machine (traveling grate, furnace downdraft)	Sintering	Iron and steel	4.87
	Sintering machine (moving grate, downdraft)	Sintering	Zinc	1.95
	Coke oven (by-product, bee-hive)	Coke production	Iron and steel	144.77
	Blast (shaft) furnace (includes blast stove)	Pig iron production	Iron and steel	267.27
	Blast furnace	Smelting	Ferromanganese	2.70
	Blast furnace	Smelting	Lead	0.12
	Blast furnace	Smelting	Tin	0.35
	Reverberatory furnace	Cathode melting	Copper	2.70
	Reverberatory furnace	Anode melting	Copper	2.52
	Reverberatory furnace (open hearth)	Steelmaking	Iron and steel	71.80
	Reverberatory furnace	Smelting	Copper	34.66
	Reverberatory furnace	Drossing	Lead	0.39
	Reverberatory furnace	Refining	Lead	0.41
	Reverberatory furnace	Refining	Silver	0.50
	Reverberatory furnace	Refining	Tin	0.34
	Reverberatory furnace	Smelting	Nickel	0.61
	Reverberatory furnace	Reducing	Nickel	0.02
	Reverberatory furnace	Refining	Antimony	0.05
	Reverberatory furnace	Reducing	Antimony	0.01
	Furnace (basic oxygen)	Steelmaking	Iron and steel	14.36
	Electric arc furnace	Steelmaking	Iron and steel	2.27
	Induction furnace	Cast iron melting	Iron and steel	16.12
	Electric arc furnace	Cast steel melting	Iron and steel	0.61
	Furnace	Electrolytic refining	Copper	6.25
	Tubular preheating furnace	Electrolysis	Magnesium	2.85
	Electric (submerged) arc furnace	Smelting	Ferrosilicon	7.15
	Electric (submerged) arc furnace	Smelting	Ferromanganese	0.33
	Electric (submerged) arc furnace	Smelting	Low-carbon ferrochromium	0.07
	Electric (submerged) arc furnace	Smelting	High-carbon ferrochromium	0.09
	Electric arc furnace	Smelting	Ferrovanadium	0.01

(Continued)

TABLE 2-2. (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Furnace (soaking pit)	Slabbing, blooming	Iron and steel	156.33
	Reheating furnace	Slabbing, blooming	Iron and steel	271.47
	Reheating furnace	Continuous casting	Iron and steel	3.42
	Heat treating furnace	Heat treatment	Iron and steel	111.52
	Cupola furnace	Cast iron melting	Iron and steel	21.71
	Core oven	Molding/core-making	Iron and steel	20.40
	Afterburner	Air pollution control	Iron and steel	5.05
	Kiln (rotary)	Calcination	Aluminum	29.95
	Kiln (rotary)	Roasting, drying	Copper	1.01
	Kiln (rotary)	Calcination	Titanium	17.60
	Kiln (rotary)	Calcination	Magnesium	1.80
	Kiln (rotary)	Roasting	Molybdenum	0.10
	Furnace (pit)	Carbon anode baking	Aluminum	11.99
	Roaster (multiple hearth)	Roasting, drying	Copper	0.50
	Roaster (multiple hearth)	Roasting	Cadmium	0.05
	Roaster (fluidized-bed	Roasting, drying	Copper	0.50
	Roaster (multiple hearth, fluidized-bed)	Roasting	Zinc	0.48
	Roaster	Roasting	Ferrovanadium	0.76
	Roaster (fluidized-bed)	Roasting	Cadmium	0.05
	Converter	Converting	Copper	1.29
	Furnace (converting)	Converting	Antimony	0.01
	Furnace (rotary)	Anode refining	Copper	2.52
	Flotation cells	Flotation	Copper	3.91
	Reactor furnace	Reduction, sintering	Titanium	0.08
	Dryer	Drying	Titanium	0.20
	Dryer (shelf)	Drying	Magnesium	4.08
	Dryer (rotary)	Drying	Zinc	0.15
	Dryer (rotary)	Drying	Ferrovanadium	0.11
	Furnace (batch, shaft)	Chlorination	Titanium	0.17
	Reaction chamber	Oxidation	Titanium	0.01
	Neutralization tanks	Neutralization, purification	Magnesium	1.69
	Submerged combustion evaporator	Evaporation	Magnesium	4.08
	Furnace (retort)	Reduction	Zinc	0.26
	Furnace (retort)	Retorting	Lead	0.01
	Furnace (retort)	Vacuum dezincing	Lead	0.15

(Continued)

TABLE 2-2. (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Furnace (retort)	Debismuthizing	Lead	0.71
	Furnace (retort)	Refining	Lead	0.12
	Furnace (pot)	Drossing	Lead	0.39
	Furnace (pot)	Desilverizing	Lead	0.33
	Reactor (batch, fluidized-bed)	Chlorination	Zirconium	0.01
	Furnace (multiple hearth)	Roasting	Molybdenum	0.10
	Furnace (dore)	Melting	Gold	0.02
	Furnace (continuous tube)	Reduction	Tungsten	0.27
	DNA	Casting/shakeout/ cleaning	Iron and steel	6.66
	DNA	Acid plant	Copper	2.18
	DNA	Acid plant	Magnesium	1.40
	DNA	Acid production	Zinc	0.02
	DNA	Acid production	Lead	0.38
	DNA	Distillation purification	Titanium	0.08
	DNA	Leaching	Titanium	0.02
	DNA	Leaching	Silver	0.16
	DNA	Leaching	Ferrovanadium	0.04
	DNA	Leaching	Gold	0.11
	DNA	Leaching	Beryllium	0.03
	DNA	Graphite electrode manufacture	Magnesium	0.31
	DNA	Graphite electrode manufacture	Ferrovanadium	0.01
	Roaster	Roasting	Silver	0.16
	DNA	Electric melting and casting	Silver	0.02
	DNA	Melting and casting	Cadmium	0.01
	Dryer	Drying, calcination	Zirconium	0.02
	DNA	Repulping, filtration, calcination	Zirconium	0.15
	DNA	Solvent extraction	Ferrovanadium	0.10
	DNA	Precipitation, filtration, fusion	Ferrovanadium	0.18
	DNA	Sintering	Beryllium	0.02
	DNA	Precipitation	Beryllium	0.03
	DNA	Filtration	Beryllium	0.01
	DNA	Partial dehydration	Beryllium	0.03

has been little incentive to recover the heat discharged in stack gases. However, with increasing fuel costs, development of high-temperature heat recovery systems has accelerated. Studies by EEA show that a significant market for these devices could exist as they become proven and are applied to both new and existing sources to conserve energy.[3]

Several energy-intensive industrial processes have been identified by EEA as capable of producing and using high-temperature preheated combustion air. Table 2-3 lists these processes.[3] The greatest energy consumption is by the steel industry in the reheating process where close to 2.5 million Btu is consumed per ton of steel and 1.4 million Btu per ton is discharged in flue gases. Simultaneously, in the soaking pits of steel mills where 75 to 80 percent of all steel is processed, 1 to 1.5 million Btu is consumed per ton while 600,000 Btu is discharged as high-temperature exhaust gas. It has been estimated that the total amount of energy expended to produce a ton of steel is close to 25 million Btu.

Although preheated combustion air presents opportunities for energy savings in industrial process heaters, it also has the drawback that increased combustion air temperatures lead to increases in thermal NO_x emitted from industrial stationary sources. NO_x emissions could increase from an estimated 6.73 million tons in 1980 to an estimated 8.31 million tons in 1990 due in part to air preheating. The purposes of this segment of the overall project were to investigate the effects of preheated combustion air on NO_x emissions from the energy intensive processes identified in Table 2-3 and to develop NO_x emission factors for these processes at various levels of combustion air preheat. Effects of heater design and operation of NO_x emissions and NO_x emission factors at various combinations of heater conditions are presented.

PROJECT APPROACH

The approach used to investigate the effects of combustion air preheat on NO_x emissions involved studies of the fundamentals of NO_x formation in direct-fired heaters, assessment of design and operating conditions of process heaters used in energy-intensive industries, and evaluation of tests of representative burners using combustion air preheat. Detailed NO_x test programs aimed at determining the effects of preheated combustion air have been

TABLE 2-3. Energy-Intensive Industrial Process Operations

Furnace	Fuel
Steel Reheat	Coke Oven Gas, Natural Gas
Steel Soaking Pit	Coke Oven Gas, Natural Gas
Aluminum Reheat	Residual Fuel Oil, Natural Gas
Aluminum Melting	Residual Fuel Oil, Natural Gas
Steel Forging	Natural Gas
Annealing	Natural Gas
Titanium Melting	Natural Gas
Nickel Melting	Natural Gas

conducted for only a small number of furnaces. Since not all furnaces used in energy-intensive processes have been the subject of NO_x emission test programs, inferences regarding the effect of preheated combustion air must be made. Therefore, the analysis consisted also of defining those parameters of furnace design that influence NO_x formation and applying the results of tests on furnaces with similar design parameters. Emission factors resulting from this analysis are based on either NO_x emission test programs or design analysis coupled with knowledge of NO_x formation fundamentals.

REPORT ORGANIZATION

Section 3 of this report contains a discussion of the fundamentals of NO_x formation in process heaters. Section 4 describes basic process heater design and operation and their general influence on NO_x formation. Section 5 describes the effect of combustion air preheat and other operating parameters on NO_x emissions for the major furnace designs identified in Section 4. Section 6 serves as a summary of emission factors developed by this analysis.

SECTION 3
FUNDAMENTALS OF NO_x FORMATION

INTRODUCTION

Regardless of the type of combustion device, oxides of nitrogen (NO_x) are formed in combustion processes by the thermal fixation of atmospheric nitrogen and by the conversion of fuel-bound nitrogen. Total NO_x emissions and the contribution of each mechanism to the total depend upon the heater design, heater operating conditions, and the type of fuel burned. Approximately 80 percent of direct-fired heaters used in manufacturing processes are fueled by oil or gas. Gas accounts for almost 65 percent, with oil at 14 percent and other fuels at a total of 21 percent. Since gaseous fuels including coke oven gas have a low fuel-bound nitrogen content, thermal fixation of atmospheric nitrogen is the dominant contributor to NO_x emissions from direct-fired heaters.

THERMAL NO_x FORMATION

Combustion generates high temperatures that result in molecular dissociation of the oxygen in the combustion air. The separate oxygen atoms react with many other atoms in the combustion reactions, but some react with the otherwise stable N_2 molecule to form NO. The chemical reactions commonly associated with NO formation are those identified by Zeldovich in 1946:[4]

$$O_2 + [M] \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} [O] + [O] + [M] \qquad (1)$$

$$N_2 + [O] \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} NO + [N] \qquad (2)$$

$$[N] + O_2 \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} NO + [O] \qquad (3)$$

In fuel-rich mixtures (oxygen deficient) an additional reaction may be important:

$$[N] + [OH] \longrightarrow NO + [H] \qquad (4)$$

In these reactions, [M] is any thermally excited molecule, [O] is free radical oxygen, [N] is free radical nitrogen, [OH] is the hydroxyl radical, and [H] is the hydrogen radical. Rate constants for the forward reactions (k_n) and for the reverse reactions (k_{-n}) are given in Table 3-1, where k_n can be represented as

$$k_n = a_n T^{b_n} \exp(-E_n/T),$$

where T is temperature in °K, a_n and b_n are constants, and E_n is the activation energy, also a constant.[3]

At combustion temperatures, the reaction (2) of molecular nitrogen with atomic oxygen to produce NO usually is much slower than the subsequent reaction of atomic nitrogen and molecular oxygen. Hence, reaction 2 controls the rate of formation of NO. The formation of an NO molecule from reaction 2, however, is accompanied by the release of an N atom, which rapidly forms ancther NO molecule by reaction 3.

Through the use of thermodynamic equilibrium and chemical kinetic analyses, it is possible to model approximately the controlling influences of combustion stoichiometry, temperature, and residence time assuming one dimensional homogeneous air/fuel flow. Under this condition, the rate expression for thermal NO formation according to the Zeldovich mechanism can be simplied as follows:

$$\frac{d\,[NO]}{d\,t} = \left(\frac{k_1}{k_{-1}}\,[O_2]^{1/2}\right)\left(\frac{2\,k_2k_3[N_2][O_2] - 2\,k_2k_{-3}\,[NO]^2}{k_{-2}\,[NO] + k_3[O_2]}\right)$$

This rate expression, derived by considering the kinetics of the three NO-forming free radical reactions, can be integrated with respect to time in order to obtain the amount of NO theoretically formed in a combustor.[3] Explicitly, the rate equation shows that the rate of formation is sensitive to the mole fractions of oxygen and nitrogen. Implicit in the values of k_n is the extreme sensitivity of NO formation to temperature. As the temperature increases, the rate constants increase in a complex exponential fashion. In general, it can be inferred from the values for k_n and the rate expression that NO formation increases with temperature in the combustion zone.

TABLE 3-1. Rate Constants for NO Formation Reactions

Rate Constant	$k_n = a_n T^{b_n} \exp(-E_n/T)$ a_n	b_n	E_n	k_n Units
k_1	5.5×10^{17}	-0.5	57,700	$cm^3\ mole^{-1}\ sec^{-1}$
k_{-1}	2.2×10^{16}	-0.5	0	$cm^3\ mole^{-1}\ sec^{-1}$
k_2	7.0×10^{11}	0.5	38,446	$cm^3\ mole^{-1}\ sec^{-1}$
k_{-2}	1.33×10^{11}	0.5	0	$cm^3\ mole^{-1}\ sec^{-1}$
k_3	2.40×10^{11}	0.5	3,321	$cm^3\ mole^{-1}\ sec^{-1}$
k_{-3}	5.0×10^{10}	0.5	19,424	$cm^3\ mole^{-1}\ sec^{-1}$

Calculations of the effect of theoretical reaction parameters, such as reactant concentrations and temperatures, on NO formation have met with limited success in predicting absolute effects over the entire range of parameters because of the very complex three-dimensional mixing that occurs in practical flames. Most combustors operate with turbulent mixing combustion flames at the burner nozzle. Turbulent eddies of air and fuel mix and then are ignited by the diffusion of excited atoms to form a primary combustion zone. Because of the strong temperature dependency, NO is produced primarily in hot combustion zones, even though there exist only small amounts of O_2. In typical hydrocarbon-air flames, $[N_2]$ is of the order of 0.7 and is difficult to modify. The $[O_2]$ is of the order of 0.01 and can be reduced by reducing the burner excess air.[5]

Analytical measurements generally indicate that reduced flame temperature, reduced oxygen in the flame, and reduced residence time at peak temperatures lead to reduced NO.

On practical equipment, analysis of combustion fundamentals of thermal NO formation involves a process of investigation of factors affecting mixing, temperatures, turbulence, heat transfer, and composition. Since preheat of combustion air can increase the peak flame temperature attained in the combustion chamber, air preheat can increase thermal NO formation. Mixing, turbulence, heat transfer requirements, and composition, however, also affect NO formation rates. Thus a quantitiative determination of thermal NO formation at various levels of combustion air preheat must be based on specific furnace designs and operating parameters.

FUEL NO_x FORMATION

Thermal NO_x formation deals entirely with NO that is formed by nitrogen and oxygen that are present in the combustion air or introduced in any manner as the stable molecules N_2 and O_2. When nitrogen is introduced in a form other than as nitrogen gas, completely different reaction characteristics can be observed. The most common form is organically bound nitrogen present in liquid or solid fuels where individual N atoms are bound to carbon or other atoms. These bonds break more easily than the N≡N bond in N_2 so that formation

rates can be much higher than for thermal NO. In fact, from one of the fuel nitrogen kinetic mechanisms, it would appear that the complex mechanism for fuel NO_x formation can be represented adequately by the almost instantaneous release of N atoms. The N atoms thus released are oxidized rapidly by Reaction 3 to NO. Thus, all fuel-bound nitrogen can be assumed to be converted rapidly to NO. As with thermal NO formation, the conversion of fuel nitrogen depends on combustion conditions. This dependency however, has been found to be less sensitive to combustion device design and operating parameters because of a lower sensitivity of reaction rates to changes in temperature and composition.[6,7,8] For this analysis, it is assumed that all fuel-bound nitrogen is converted to NO with no affect by combustion air temperature. Figure 3-1 provides the NO_x emission factor incremental contribution from the fuel-bound nitrogen.

OXIDE FORMS

Forms of oxides of nitrogen, other than NO can be generated in combustion. In general, NO is found to be the predominant form. However, NO_2 is usually observed at about 3 to 6 percent of total NO_x. In the atmosphere, most NO eventually is converted to NO_2, which is the compound that has been of most concern for air quality and on which the ambient air quality standards are based.[5] For the purposes of this study all NO_x emissions are expressed on the basis of NO_2 to remain consistent with air quality standards.

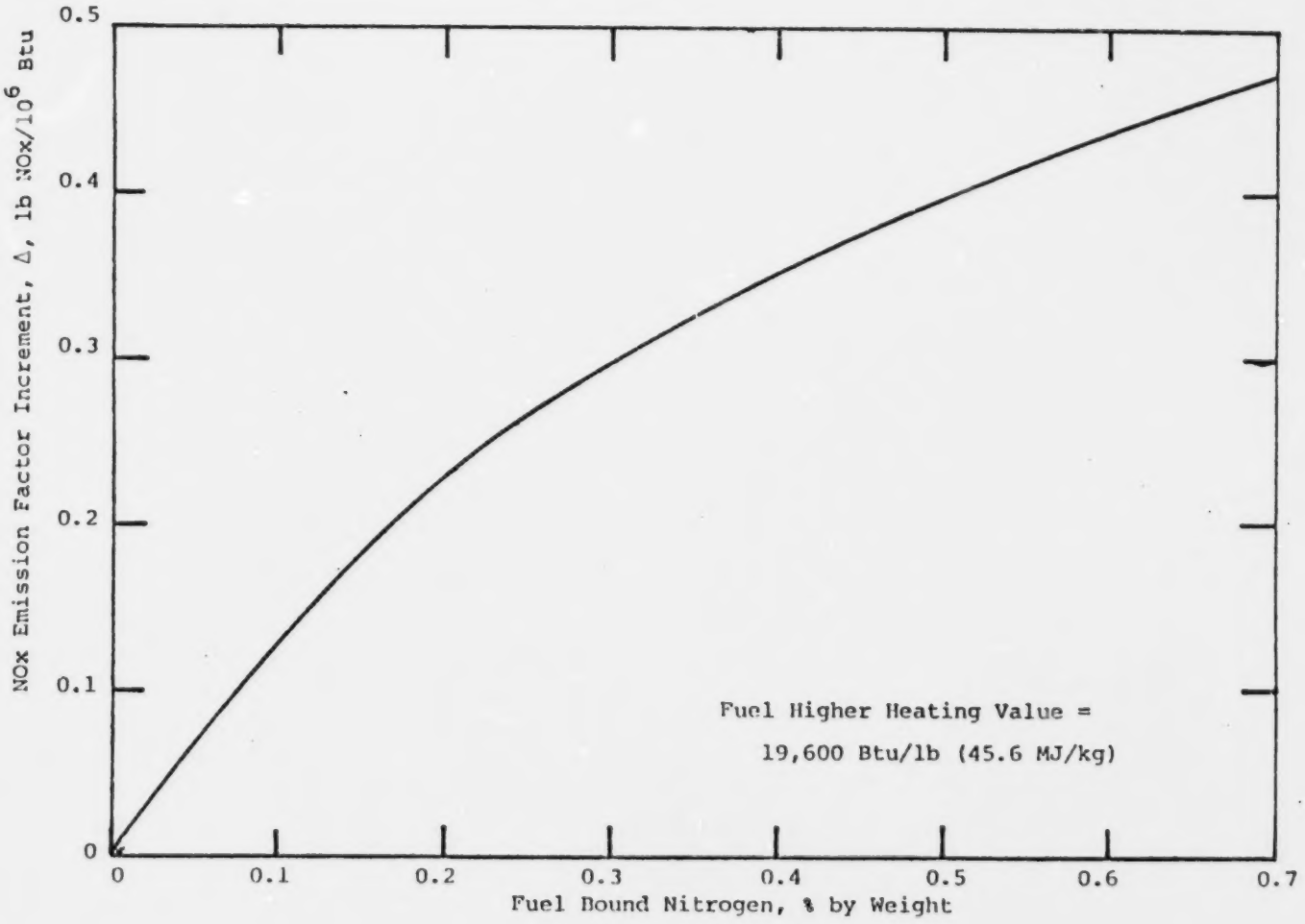

Figure 3-1. Fuel bound nitrogen effect on NO_x emission factor.

SECTION 4

PROCESS HEATER DESIGN AND OPERATION

PROCESS HEATER OPERATION

The primary function of process heater systems is to provide controlled efficient conversion of the chemical energy of fuel into an energy form that can be transferred as heat to process fluids. Process heaters do this by introducing the fuel and air for combustion, mixing these reactants, igniting the mixture, and distributing the flame envelope and the products of combustion.

A fuel burning system prepares fuel and air for combustion, properly directs their introduction into the furnace, provides conditions for stable ignition and combustion, and suitably removes the products of combustion from the furnace.

The process heater should function so that the fuel and air input is ignited and burned continuously and immediately upon its entry into the furnace. The total fuel burning system required to do this consists of subsystems for air handling, fuel handling, ignition, and combustion product removal plus the burners and the furnace.

The goal of process heater design is to ensure that each heater subsystem can provide the conditions necessary for efficient combustion of fuels. In the strictest sense, a fired heater performs its service according to the cooperation between process design and the manner in which the heater is being fired. To separate the design parameters and the operating conditions of the heater is virtually impossible. For the sake of discussion, however, the furnace may be assumed to be designed to allow for optimum heat transfer and operated to achieve the optimum efficiency in transferring this heat.

This section describes the important design parameters of direct-fired heaters and their influence on the formation of oxides of nitrogen. In addition designs of specific furnaces identified as energy intensive are

discussed and grouped according to similarities of design parameters that influence NO_x formation. Finally, design modifications aimed at energy conservation, primarily combustion air preheat, are discussed.

BURNER DESIGN

The function of the burner equipment is to deliver heat to the gas content of the furnace as uniformly as possible to produce a temperature contour throughout the mass of the furnace gases which is as nearly even as possible. The burner equipment used must disperse heat to the gaseous furnace atmosphere if the heater is to be satisfactory. It is the relative ability to disperse heat by a particular burner that may make it suited to firing a specific heater. If the burner is applied to another furnace having a different configuration, it may be quite unsatisfactory.

Burner flames must be shaped and directed to allow the required heat diffusion to the furnace gases without delivering excessive heat to any transfer area. At times, the flame shape is that of a rigid cylinder of quite small diameter and great length. At other times, the flame is in the form of a less rigid cylinder of greater diameter and lesser length. Other flames must be still less rigid and of still greater diameter to the point where there is no flame rigidity and where the flame moves at right angles to the burner axis and against the furnace wall with zero length or forward motion. At times the flame may be required to be in the shape of a fan, narrow at the bottom and wide at the top viewed in elevation but quite thin in cross section. Fan shapes allow firing of quite long but relatively narrow spaces without heat damage to transfer surface.

A burner is a device made of metals and refractory, which accepts specific amounts of air and fuel and mixes them as homogeneously as possible and then causes the fuel to burn through stable exothermic chemical processes. Mixture must precede burning. The state of mixture determines what state of burning may exist. Thus, it is the function of the burner to ensure (1) proper mixing of combustion reactants; (2) continuous combustion reactions; and (3) proper heat dispersion by regulating the size and shape of the flame envelope. Therefore, since NO formation is governed by flame temperature, turbulence or mixing, and the time N_2 and O_2 are held at the flame temperature,

the burner design greatly influences NO_x formation. Although other factors are necessary for proper heater design, such as refractory material and overall furnace layout, the burner is chosen to compliment the additional factors and thus reflect their influence on combustion. By analyzing various furnaces on the basis of burner design alone, trends in NO formation can be assessed for many different furnace types.

In the broadest sense, burners (particularly gas burners) are offered as either premix or nonpremix (raw gas) types. The term premix denotes an operating condition where a portion or all the air for burning is mixed with fuel before the fuel reaches a point at which burning can begin. Nonpremix burners cause the air-fuel mixture to occur coincidentally with burning. Oil burners are generally of the nonpremix type, unless the oil as a liquid can be converted to oil as a vapor immediately prior to burning

There are many burner manufacturers but the number of basic burner designs is limited. Any burner conforming to basic design parameters will have heat dispersive characteristics typical of the basic design configuration, regardless of the manufacturer or specific heater use.

Assuming that burners are chosen properly in furnace designs, trends in NO formation can be evaluated for many various types of furnaces by analysis of the few basic burner types. The following subsection describes the furnace designs and burner types used in energy-intensive applications under consideration.[9]

AIR PREHEAT BURNER DESIGNS

The national waste heat inventory prepared by EEA indicates that the best potential for the application of waste heat recovery within the manufacturing sector lies in the following industrial groups: refining; stone, clay, and glass; primary metals; and fabricated metals.[3] The inventory reveals significant amounts of waste heat from many processes, such as steel, aluminum, glass and cement. In order to assess the environmental consequences of recovery of this heat by preheating combustion air, the furnaces used in these industries must be analyzed in terms of their basic design and burner use.

At present, only a few burner types are available for use with high temperature preheated combustion air. Standard burners can be modified slightly to handle limited amounts of preheated air. High temperature preheat of combustion air, however, is not possible with these modified standard burners.

The major limitations on the development of high temperature burners stem from lack of demand and difficulty in obtaining appropriate construction materials. The demand for high temperature combustion air preheat combustion equipment is related closely to the demand for waste heat recovery devices. As fuel prices increase and fuel becomes scarce, the economics of energy conservation should favor use of waste heat recovery.

There are three different temperature ranges for preheated combustion air. Generally, low temperature air preheat is the most efficient. The benefit gained by an increase in air preheat temperature from ambient to 500°F is greater than the incremental benefit gained between 500 and 1000°F. Likewise, the 500 to 1000°F temperature increase is more efficient than the 1000 to 1500°F and higher increase. For the energy-intensive industries under consideration, many plants already employ some degree of combustion air preheat above ambient levels. Thus, the increment of preheat from 500°F to 1000°F and slightly beyond appears to be the level of preheat expected in the processes under consideration.

There are three critical temperatures that divide the attainable levels of combustion air preheat:[3]

- The upper limit or failure point for ambient air systems is 750°F.
- The upper limit or failure point for most modified steel systems is 1000-1200°F.
- The upper limit or failure point for the majority of custom-made high temperature systems is 1400-1600°F. New custom-made systems may be able to employ combustion air at temperatures over 2000°F with special designs.

The currently manufactured high temperature burners have difficulty generating all the flame types used in industry. A short, flat flame, for example, cannot be generated using preheated combustion air, because the high

temperature zone is too near the nozzle. While ordinary burners may be able to change from one flame type to another without harming the burner, high preheat temperatures and resulting high flame temperatures usually are not feasible with current burner design. Thus, the direct-fired process heaters that can employ higher levels of combustion air preheat must possess furnace designs compatable with the flame and heat dispersive characteristics of the burner.

Most standard industrial burners are fabricated from either cast iron or carbon steel. At temperatures in the 500 to 750°F range, both materials show signs of growth and distortion. These dimensional changes in materials alter orifice sizes, cause joints to break, and usually lead to burner failure.

As the temperature of the combustion air increases, the amount of fuel necessary to maintain a given furnace production rate decreases. When the amount of fuel decreases, the amount of air necessary to combust the fuel also decreases. As the required mass of air decreases and the temperature increases, the density of the air decreases.

Air mass requirements can be lowered by air density diminishing at a faster rate than increasing fuel efficiency. At higher air temperatures, the flow rate of air must increase. This increase causes a much larger pressure drop across the burner. The end result may be burner instability due to high air velocity and inability of the combustion air supply source to meet the new burner pressure requirements. It also may be necessary to increase blower size in forced draft furnaces or increase blower capacity in natural draft furnaces in order to increase the air flow rate.

When using air preheat temperatures in the 750 to 1000°F range, most manufacturers suggest using stainless steel burner models with modifications. Stainless steel is usually nickel chromium alloys, which have high resistance to oxidation and corrosion. This resistance to oxidation is important because the oxygen in combustion air attacks steel when the temperature rises. The stainless steels used in burners usually are 300 series alloys and are reliable at temperatures well above 1000°F. It is unnecessary to fabricate the entire burner from these alloys--only those components that contact either the high temperature air or the flame itself.

When operating at high air preheat temperatures, it is important to insulate the fuel supply from the heat of the air supply. If the fuel supply rises above 700°F, cracking of hydrocarbons becomes a potential problem. The result of cracking is carbon deposits in the fuel line and in the fuel orifices. Both of these problems hinder burner operation by altering the fuel flow pattern. The effect of adjacent high temperature air lines on the fuel supply system depends to a large extent on the fuel velocity. The longer the fuel remains in contact with the hot air, the greater the possibility of cracking. The influence of the hot air is tempered by the nature of the materials that separate it from the fuel. In many instances, a refractory is used to insulate the fuel line and the outside casing from the hot combustion air.

Another design problem that occurs in high temperature preheat burners involves the control of turbulence. If there is insufficient turbulence, fuel cracks without burning upon leaving the nozzles. The soot that is formed from cracking can clog the fuel orifice. If the turbulence is too high, then the fuel mixes too quickly, and it becomes difficult to lengthen the flame.

REPRESENTATIVE BURNERS

Several major companies are involved in the manufacture of burners capable of accepting high temperature combustion air. In order to evaluate the effect of combustion air preheat on NO_x emissions from direct-fired process heaters, burners must be selected as representative of the burners that are used or potentially could be used for the specific furnaces under consideration. Steel reheating processes, steel soaking processes, and aluminum melting processes can be represented by the Bloom hot air baffle burner based on its extent of use in these processes currently. Because of process similarity and furnace design and operation, the Bloom hot air baffle burner would be representative of the nickel and titanium melting furnaces also. The Bloom burner also is used in refinery process heaters. The North American refractory-lined burner is used in the glass industry, and because of similar process heat requirements, it also may be considered as

representative of burners used in cement kilns. The similarities in process and flue gas temperatures supporting the assignment of these two burner types is shown in Table 4-1. Thus, by analysis of the various operating conditions of two burners, the effect of combustion air preheat on NO_x emissions from energy-intensive processes can be estimated.

TABLE 4-1. High Temperature Industrial Processes

Industry	Process	Process Temperature (°F)	Estimated Flue-Gas Temperature, (°F)
Iron and Steel	Reheating	2400	2000-2200
	Soaking	2400	2100-2400
	Forging	2200	2000
Aluminum	Melting	--	2100-2400
Titanium	Melting	--	--
Nickel	Melting	--	--
Petroleum Refining	Process Heating	1250-1600	--
Cement	Calcining	2500-2800	2300
Glass	Melting	2800	2600

SECTION 5

EFFECT OF HEATER OPERATION ON NO_x EMISSIONS

As noted in the discussion on NO_x formation mechanisms, the amount of NO_x formed in the combustion zone of a process heater is influenced by the combustion temperature, the turbulence of the reaction zone, and the residence time at the combustion temperature. The operating parameters of process heaters determine, to a large extent, the temperature, turbulence, and reaction time of air and fuel in the combustion zone.

As industries seek ways of reducing operating costs by fuel conservation, adjustment of operating parameters for optimum fuel conservation may be performed. Optimization of fuel use using heat recovery techniques, however, may lead to increases in pollutant emissions. Currently, one of the more prevalent heat recovery techniques involves preheating combustion air to achieve greater furnace efficiency. This air preheat also increases NO_x formation by increasing the temperature in the combustion zone. A systematic study of energy-intensive industries reveals two broad, distinct classifications for industrial processes capable of using preheated combustion air. The steel, aluminum, and other metal processes and petroleum refining use baffle burners capable of using air preheat in the range of 800-1200°F. Furnaces common in the glass manufacturing and cement manufacturing industries can use preheated combustion air in the range of 1600-2200°F.

This section discusses the quantitative effects of combustion air preheat on NO_x emissions. Results of both theoretical combustion studies and NO_x emission test programs are described. Other techniques used in conjunction with combustion air preheat to reduce NO_x formation also are described.

THEORETICAL CONSIDERATIONS

Based upon the Zeldovich reaction mechanism, a simple thermal NO formation model was developed in which the amount of NO formed depended upon the temperature profile, the concentration profiles of reactants, and the residence time in the combustor. This model assumed one-dimensional homogeneous plug flow of combustion gases along the length of a combustor, and the temperature was assumed to vary only along the combustor length.[3]

The NO kinetics model, described by the differential rate expression for the Zeldovich mechanism presented in section 3, was applied to natural gas combustion data developed by the Institute of Gas Technology (IGT). The data in Table 5-1 were collected on an experimental IGT furnace burning natural gas from a forward flow burner similar to those used in steel reheat furnaces. The temperature profiles in the furnace under the conditions given in Table 5-1 and as measured by IGT are given in Figure 5-1.

The isothermal profiles in Figure 5-1 were converted intc a unidirectional profile with respect to residence time in the furnace. The mole fractions of nitrogen at the furnace entrance and at the exit are about the same. The mole fraction of oxygen changes from about 0.192 at entrance to about 0.018 at exit. All combustion reactions are completed at the point where flame ends. It is assumed that oxygen concentration drops linearly with distance during combustion.

A computer program was developed to calculate thermal NO_x formation according to the rate expression given previously. The residence time of combustion gases in the furnace was calculated from the average linear velocity of the combustion gases in the combustor. This residence time was the upper limit for the integration of the NO rate expression.

Preheating combustion air increases the flame temperature and heat radiation from the combustor flame and reduces the amount of energy lost with final flue gases. This enables fuel consumption to be reduced. However, the reduction in fuel flow and the corresponding reduction in air flow lead to an increase in the residence time in the combustor. The thermal NO production may increase due to an increase in the flame temperature as well as residence time.

TABLE 5-1. IGT NATURAL GAS COMBUSTION DATA

Fuel Flow	5,140 SCF/hr
Air Flow	53,960 SCF/hr
Air Preheat Temperature	650°F
Flame Length	180 cm
Furnace Length	426 cm
Furnace Cross-Section	140 x 140 cm^2
Flue gases	59,000 SCF/hr
Flue Gas Temperature	2433°F
CO_2 in Flue Gases	10.9% (dry basis)
O_2 in Flue Gases	2.0% (dry basis)
N_2 in Flue Gases	87.0% (dry basis)
NO_x in Flue Gases	300 ppm

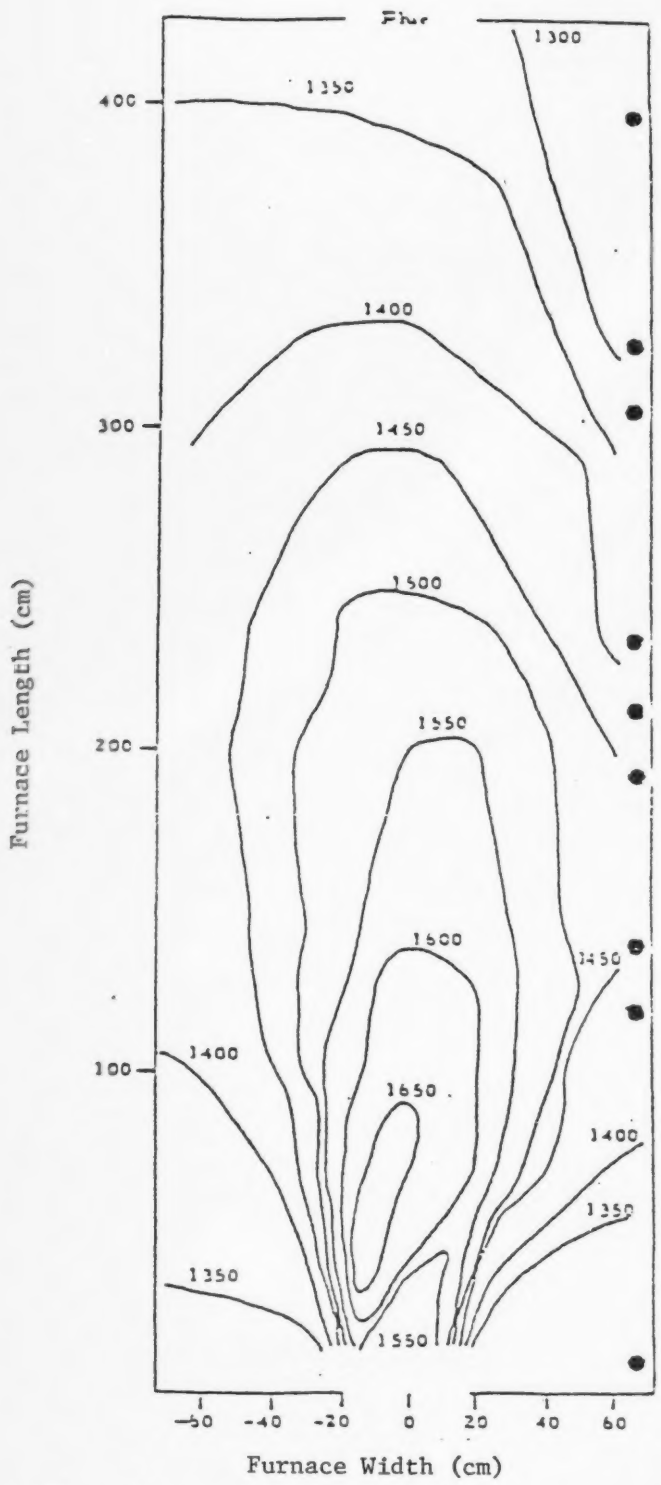

Figure 5-1. Iso thermal Profiles in the IGT Furnace (°C)

The residence time data for natural gas listed in Table 5-2 for different air preheat temperatures were calculated from an energy conservation model of a furnace developed by EEA. These data were applied to the IGT furnace and burner described previously. The fuel flow and air flow data in Table 5-2 are hypothetical and were calculated from the residence time data of Table 5-3.

In order to project thermal NO_x emissions for different degrees of air preheat, the following assumptions were made:

- The flame length is the same for all cases, and the peak temperature occurs at the same point in the furnace for all cases.
- The temperature at the burner end of the furnace is 100°C below the peak temperature, and the temperature at the flue gas exit end of the furnace is 350°C below the peak flame temperature.

The NO_x emission results calculated for different air preheat temperatures are listed in Table 5-2 and plotted in Figure 5-2.

The amount of NO formed as calculated by this model may vary from reality because of the following model limitations:

- The temperature profiles estimates may not be accurate.
- The model does not take into account the effect of backmixing of combustion gases and the resulting increases in residence time.
- It does not take into account the temperature and concentration variation in a three-dimensional space.

Regardless of these limitations, the model does provide a framework for qualitative assessment of the effect of combustion air preheat on NO formation. Thermal NO_x emission estimates are very sensitive to the temperature profile data of the combustors and will increase almost exponentially with increasing air preheat temperature.

Perhaps the most significant limitation of the model for quantitative NO_x emissions prediction is the unaccounted for effect of backmixing, leading to an increase in residence time. Since NO_x formation should vary directly with residence time, actual test data can be used to calibrate the model by development of a residence time (backmixing) correction factor. The following sections describe results of NO_x emission test programs for model calibration.

TABLE 5-2. THEORETICAL EFFECTS OF COMBUSTION AIR PREHEATING ON NO_X EMISSIONS

Fuel Flows (SCF/hr)	Air Flow (10% Excess) (SCF/hr)	Air Preheat Temperature (°F)	Peak Temperature in Furnace (°K)	Residence Time (SEC)	NO* (wet basis) (ppm)	NO_2 (lb/10^6 Btu)
5,140	53,173	600	1830	18.18	35	0.051
4,283	44,311	1000	1897	21.82	166	0.241
3,984	44,311	1200	1927	24.00	326	0.474
3,954	37,184	1400	1956	26.00	601	0.873
3,338	34,528	1600	1983	28.00	1024	1.489
3,134	32,423	1800	2009	29.81	1620	2.354

* Basis: 2.0 percent oxygen in flue gases.

TABLE 5-3. THEORETICAL AIR PREHEAT DATA FOR NATURAL GAS

Air Preheat Temperature (10% Excess Air)	Residence Time Relative to 600°F Residence Time	Peak Temperature (80% of adiabatic Flame temperature)
°F		°F
600	1.0	2834
800	1.1	2895
1000	1.2	2954
1200	1.32	3009
1400	1.43	3061
1800	1.54	3110
1800	1.64	3.56

Natural Gas Composition:

CH_4	90% by Volume
C_2H_6	5% by Volume
N_2	5% by Volume

Flue Gas Composition:

CO_2	8.77% by Volume
H_2O	17.09% by Volume
O_2	1.73% by Volume
N_2	72.41% by Volume

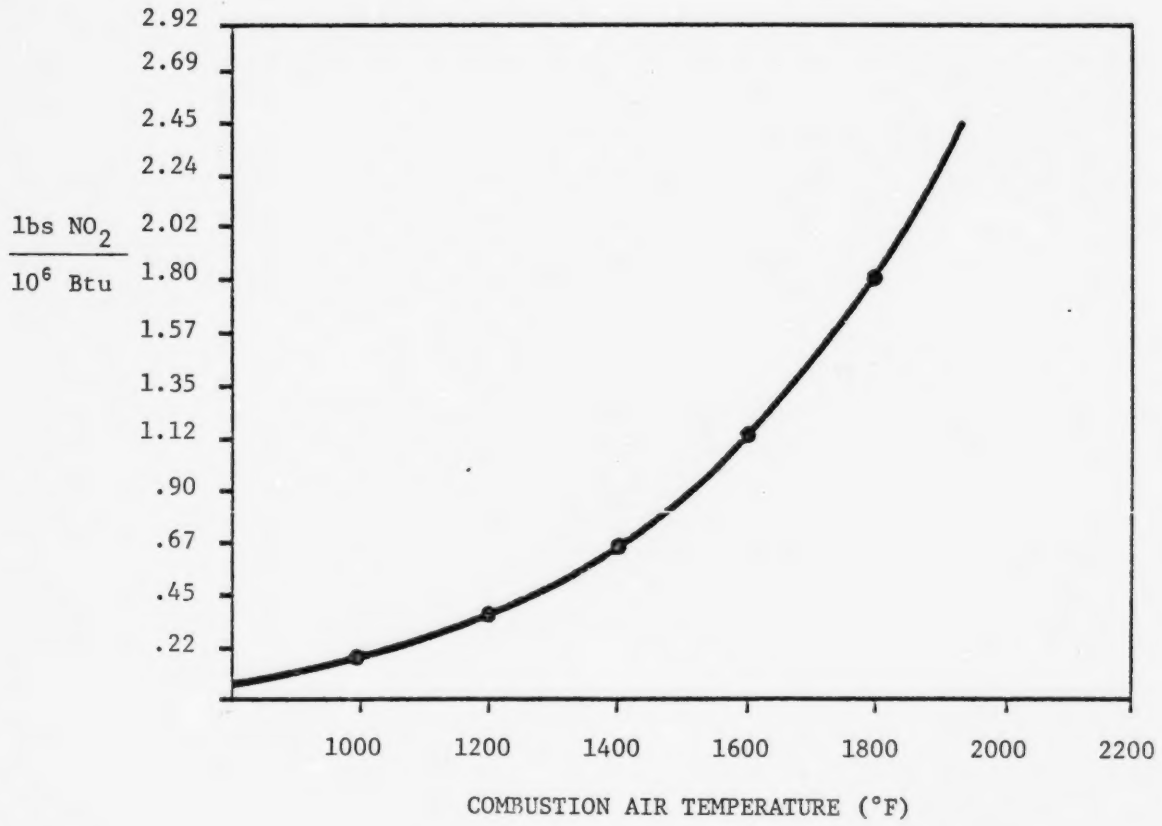

Figure 5-2. Theoretical Effect of Combustion Air Preheating on NO_x Emissions

EMISSIONS TEST PROGRAM

A study was conducted by IGT to evaluate the environmental and economic trade-offs associated with the application of NO_x control methods to industrial furnaces using preheated combustion air.[10] An integral part of this study involved the quantitative determination of the effect of combustion air preheat on NO_x emissions. In addition, this program also evaluated the effects of low excess-air firing (0 to 35 percent) and flue-gas recirculation (5, 10, and 20 percent) on NO_x emissions for combustion air temperatures of 800°F, 1000°F, and 1200°F. These tests were conducted in a pilot-scale furnace using a hot air-baffle burner, which is representative of burners widely used in high-temperature energy-consuming industrial processes in the primary metals industry.

Many industrial processes, such as regenerative glass melters and cement kilns, operate with combustion air temperatures significantly higher than primary metal industries. Combustion air temperatures of 2000°F to 2200°F are common for regenerative glass melters. NO_x emissions data for combustion air temperatures of 1600°F to 2200°F were collected from a one-quarter scale glass melter port on a pilot-scale furnace. The burner port was designed in consultation with a representative of the container glass manufacturers industry, and the NO_x emissions data were collected at furnace operating conditions similar to those found in glass melters. The effects of stoichiometric ratio (fuel rich to 8 percent excess oxygen), fuel injection velocity (67 to 190 ft/sec), firing rate (3.0 to 2.2 million Btu/h), and flue-gas recirculation (5 and 10 percent) on NO_x emissions were investigated.

The results of these investigations and additional research on low-NO_x burner development described later form the basis for the quantification of NO_x emissions from processes using high-temperature combustion air.

Metal Industry Test Facility

The Bloom hot air-baffle burner was selected for testing because of its widespread use throughout industry in high-temperature, energy-intensive processes. Figure 5-3 is a cross section of the Bloom burner, and Table 5-4 gives the nominal operating conditions of the burner.

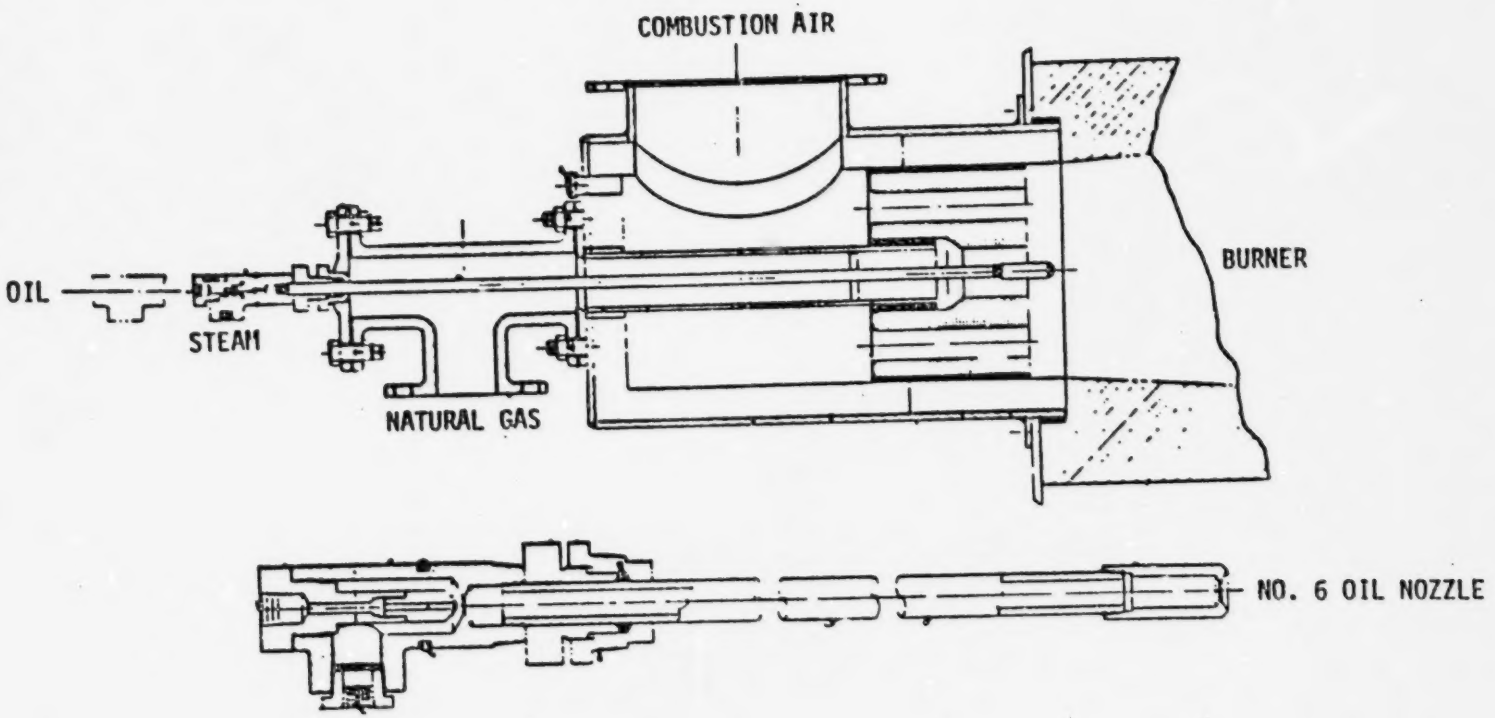

Figure 5-3. Bloom 1201 Series FTR Hot Air Baffle Burner
Source: Reference 10

TABLE 5-4. NOMINAL OPERATING CONDITIONS OF BLOOM BASELINE BURNER

Nominal Capacity	4.9×10^6 Btu/hr
Air Inlet	10 in. diameter
Gas Inlet	2 in. diameter
Natural Gas Flow	4890 SCF/hr
Natural Gas Pressure	3 in. wc
No. 6 Oil Flow	32.6 gas/hr
No. 6 Oil Pressure	90 psig
Steam Flow	98 lb/hr
Steam Pressure	90 psig
Combustion Air Flow	53,790 SCF/hr
Combustion Air Pressure	6 in. wc at 750°F

IGT furnace No. 1 was used for the tests. The furnace is 3 feet high, 4-1/2 feet wide and 14 feet long (internal dimensions) and is lined with 3200°F hard refractory. It is equipped with 31 removable panels along one sidewall to allow for insertion of gas-sampling probes into any part of the combustion chamber. The furnace is equipped with water-cooling tubes that can be inserted through slots in the roof along the sidewall to simulate a load. The furnace is equipped to handle the combustion of natural gas, oil, or low-Btu gas. Figure 5-4 is a diagram of the overall furnace system.

The combustion air system for the laboratory furnace can supply 30,000 SCF/hr of 1200°F preheated combustion air with a separately fired radiant tube air preheater. The radiant tube air preheater is an insulated, airtight, steel chamber, 4 feet high, 4 feet wide, and 16 feet long. The combustion air is heated by passing over three 6-inch diameter "hairpin" gas-fired radiant tubes.

The flue gas recirculation system for the furnace is designed to allow for up to 30 percent recirculation of cooled flue gases into the combustion air system. The flue products are drawn through a short length of internally insulated steel duct and on through to a packed-bed water cooler. The gases are cooled in the packed bed to approximately 125°F, and the water content of the flue gases is reduced. From the packed bed, the flue products are drawn through to the combustion air fan, mixed with the combustion air, and passed through the preheater to the furnace.

Glass Melter Furnace

Tests of the effect of various operating parameters on NO_x emissions from glass melter furnaces were conducted on a pilot-scale furnace located at IGT's Energy Development Center. The burner used was a 1/4-scale glass melter port equipped with two gas nozzles mounted in the sides of the port. The combustion air was preheated in an indirect-fired radiant tube preheater up to 1110°F and then by a direct-fired air heater to the required temperatures of 1600°F to 2200°F.

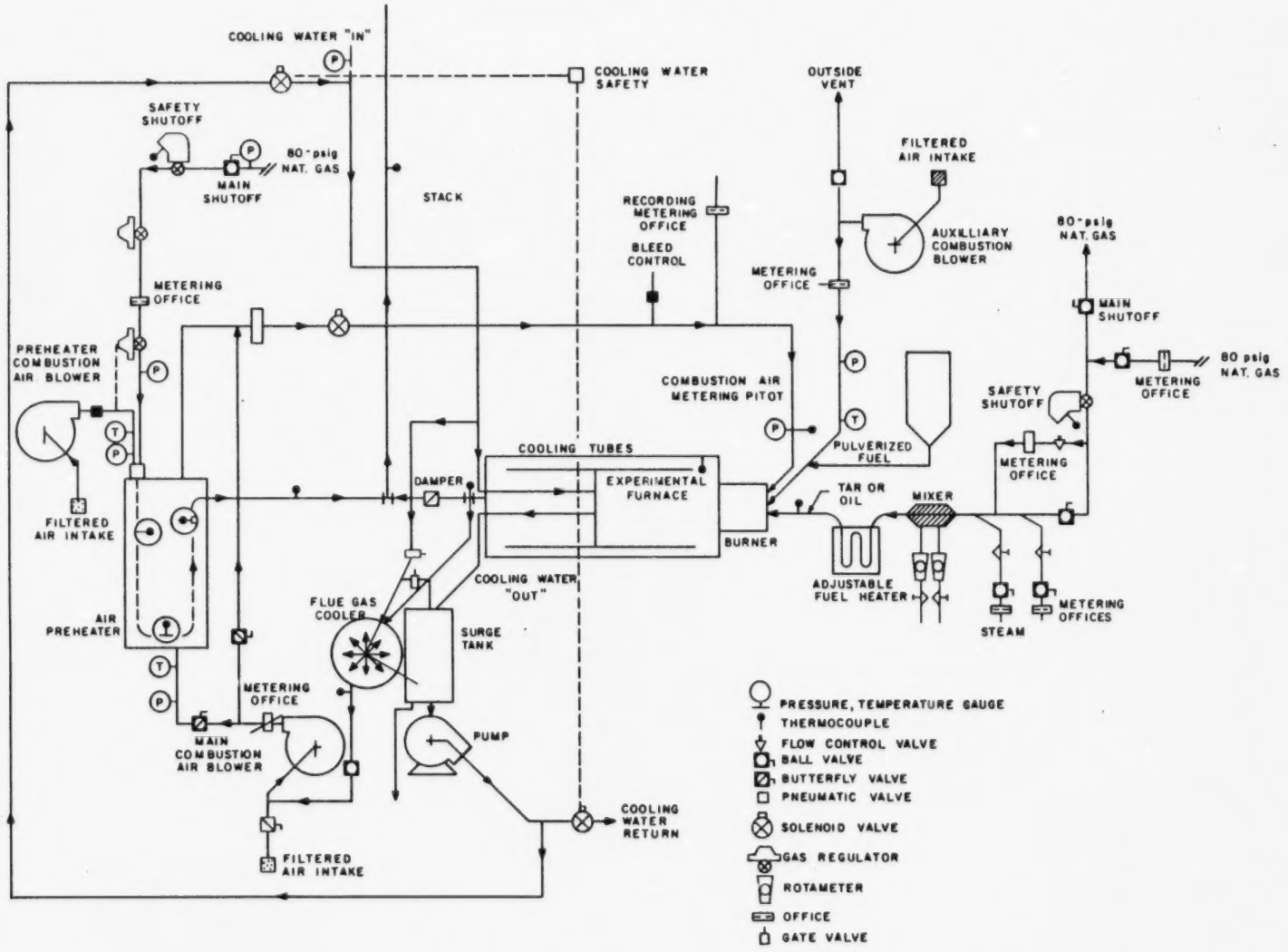

Figure 5-4. Overall Furnace System; Source: Reference 10.

The internal dimensions of the furnace are: height, 3 feet; width, 4-1/2 feet; and length, 14 feet. The furnace is lined with 3200°F hard refractory and has 30 removal panels along one sidewall for the insertion of gas sampling and temperature measuring probes.

Water-cooled tubes can be inserted through ten slots in the roof along the sidewalls to simulate a variety of load patterns.

The burner used for the high combustion-air preheat (1600°F to 2200°F) tests was 1/4-scale, side-fired, glass melter port. The sidewalls and the floor of the port were fabricated from high-temperature firebricks, and the roof and the blocks for the burner nozzles were fabricated from high-temperature heavy castable refractory. The port was designed to give a velocity of 25 ft/sec when firing 3 million Btu/h natural gas with 15 percent excess air at 2200°F. This velocity is close to that found in actual glass melter ports. The two gas nozzle blocks were designed for a 90-degree angle between the nozzles so that the axis of the nozzles converged to a point close to the port exhaust.

The gas nozzles were standard pipes. Initially 1/2-inch schedule 40 steel pipe was selected as the standard nozzles, providing a fuel injection velocity of about 200 ft/sec; these nozzles resulted in flames that were shorter and more intense than desired. Later 3/4-inch schedule 40 steel pipe was used as the standard nozzles for the bulk of the tests. The 3/4-inch nozzles gave a fuel injection velocity of 110 ft/sc. Figure 5-5 is a side view schematic of the furnace, glass melter port and direct-fired heater.

EMISSION TEST RESULTS

Bloom Hot-Air Baffle Burner

The results of NO_x emission tests on the Bloom hot-air baffle burner system, representing the metal industries, indicated an increase in both NO_x formation and fuel savings with an increase in preheated combustion air temperature. Low excess-air firing decreased NO_x formation and also increased fuel savings. Flue gas recirculation, which was investigated also, showed a much greater impact in reducing NO_x emissions than low excess-air firing; however, there is a corresponding increase in cost associated with a decrease in furnace efficiency and large capital expenditure for equipment and control.

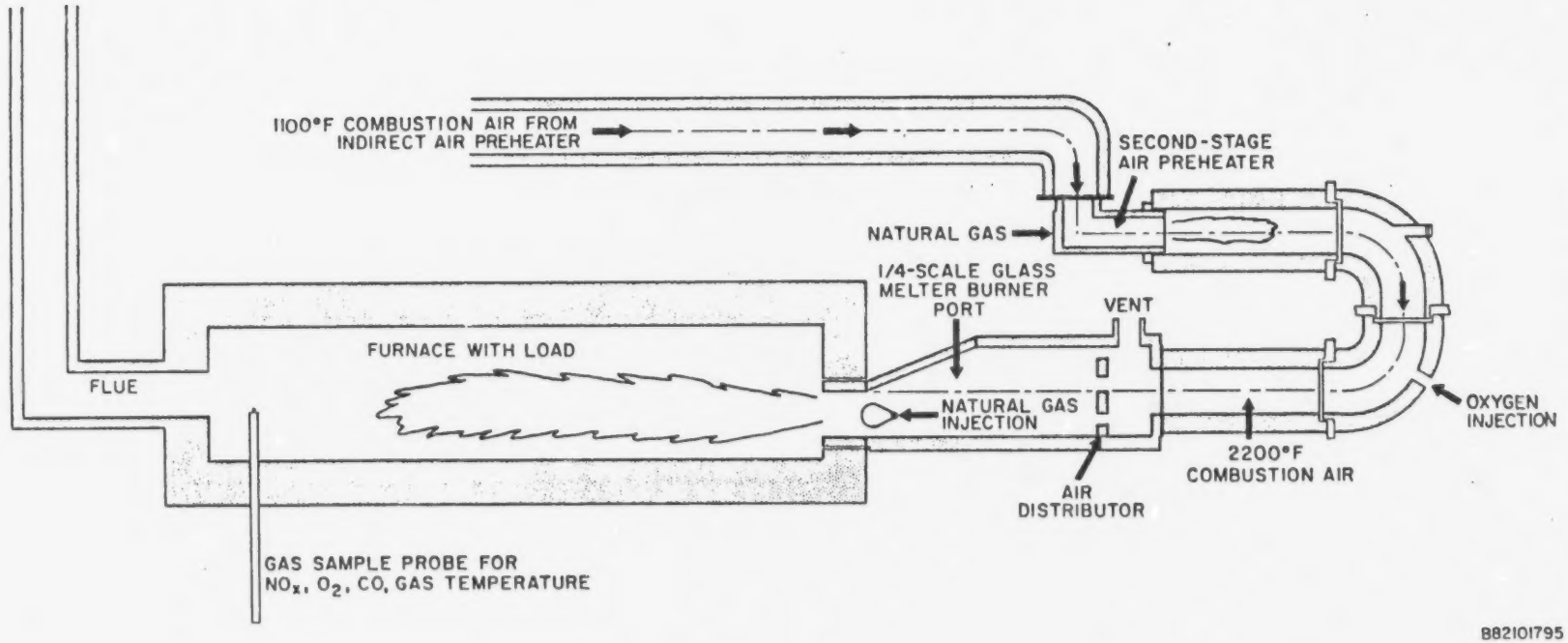

Figure 5-5. Side View Schematic Drawing of Furnace, Glass Melter Port and Direct-Fired Heater
Source: Reference 10

The following conclusions are based on the results of the IGT emission test program on the Bloom hot-air baffle burner:

- NO_x formation expressed as parts per million increases exponentially with an increase in combustion air temperature in the 800°F to 1200°F temperature range.
- The rate of NO_x formation peaks in the 25 to 30 percent excess air range (5 to 7 percent excess oxygen range).
- Low excess-air firing significantly reduces NO_x formation, especially at higher combustion air temperatures.
- Furnace efficiency increases with preheated combustion air in the 800°F to 1200°F temperature range.
- External flue-gas recirculation provides an effective means to reduce NO_x formation. Flue-gas recirculation is more effective at higher air temperatures.
- External flue-gas recirculation and low excess-air firing produce an additive effective on NO_x formation.
- NO_x formation expressed as pounds of NO_2 per million Btu heat absorbed do not increase as rapidly with combustion air temperature as NO_x emissions expressed as pounds of NO_2 per million Btu fuel input. This is because furnace efficiency increases and the fuel consumption per unit of production decreases as the combustion air temperature is increased.

Data presented in this subsection were collected with furnace load and operating conditions set to simulate a steel soaking pit. The furnace operating conditions are shown in Table 5-5. Because of process requirement similarities, these data also should represent combustion in furnaces present throughout the metals industries.

Table 5-6 shows the results of combustion air temperature tests. Data were collected for combustion air temperatures ranging from approximately 650°F to 1200°F and 10 percent excess air. Figure 5-6 shows the relationship between NO_x expressed as pounds of NO_2 per million Btu fuel fired and temperature. Increases in combustion air temperature leading to increases in peak flame temperatures cause increases in the rate of NO_x formation. Although predictive theory indicates that NO_x formation should exhibit a definite exponential relationship, within the 650°F-1200°F temperature range, a linear relationship can be used to describe the variation of NO_x formation with combustion air

TABLE 5-5. SOAKING PIT FURNACE OPERATING CONDITIONS USING 650°F, 800°F, and 1200°F COMBUSTION AIR

Combustion Air Temp., °F	Natural Gas Flowrate, SCF/hr (10^6 Btu/hr)	Excess Oxygen, %	Furnace Load Absorbed, Btu/hr	Furnace Efficiency, %	Flue Temp., °F
650	2612 (2.68)	2.1	0.93	34.82	--
664	2612 (2.68)	2.2	0.91	34.07	2196
805	2574 (2.65)	2.5	0.94	35.50	2181
999	2574 (2.65)	1.8	1.01	38.00	--
1193	2373 (2.44)	2.3	9.39	38.43	2247
1192	2373 (2.44)	2.2	9.61	39.32	2300

TABLE 5-6. EFFECT OF PREHEATED COMBUSTION AIR ON NO_x EMISSIONS

Combustion Air Temperature (°F)	NO_x, ppm, corrected to 0% excess air	NO_x (lbs/10^6 Btu)
650	217	.220
664	203	.206
805	290	.294
999	470	.477
1193	663	.673
1192	794	.806

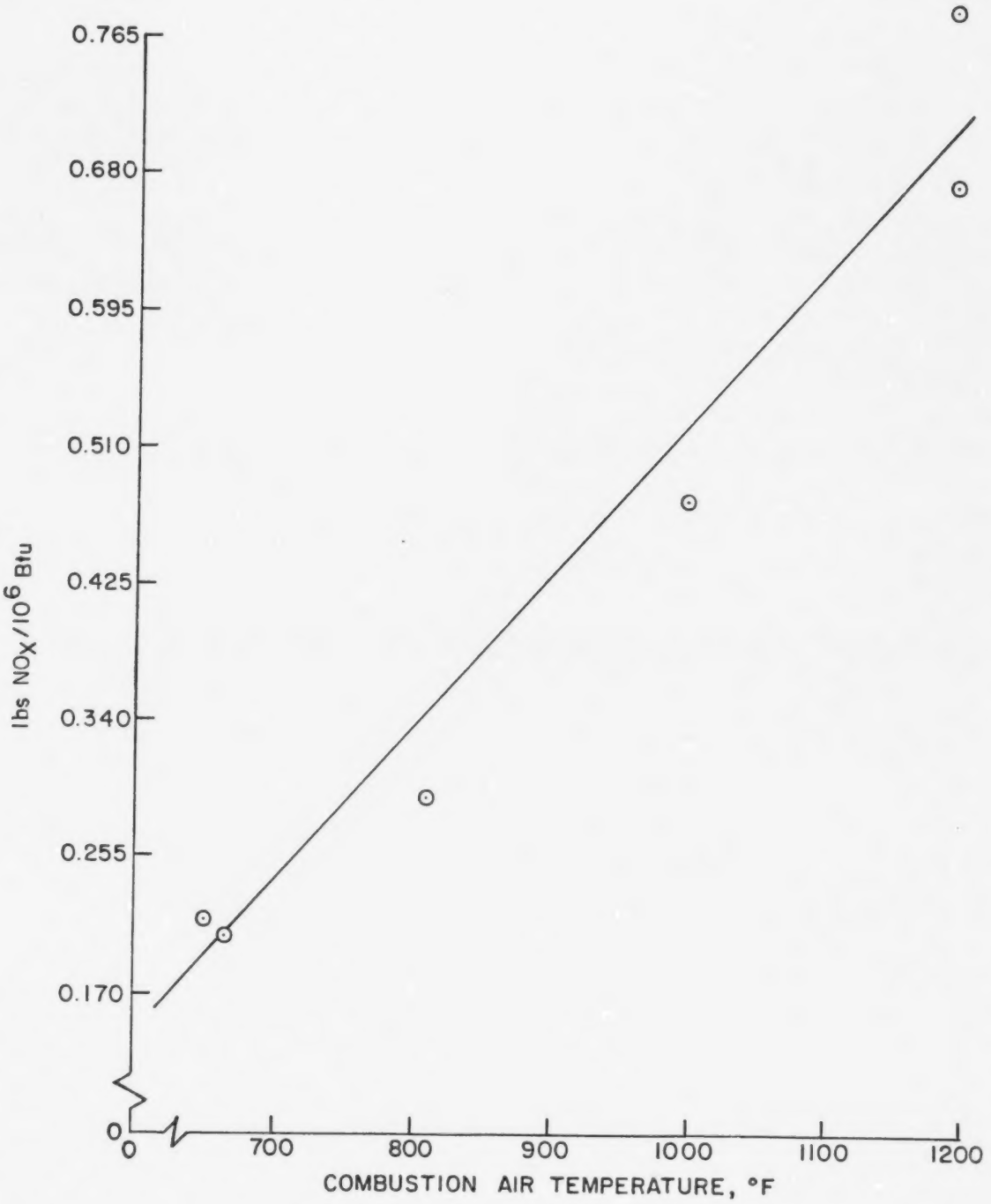

Figure 5-6. Relationship between No_x emission factor and combustion air temperature.

temperature. This simple linear relationship shows a correlation coefficient of 0.975. Due to the relatively small range of temperature values tested, it is not possible to predict NO_x formation rates for any combustion air temperature above 1200°F.

The effect of excess air on NO_x formation for various combustion air temperatures also was studied. At low excess air levels (approximately stoichiometric), thermal NO_x formation was suppressed by limiting the local concentration of oxygen. NO_x formation increased as the excess oxygen increased, and the greatest amount of NO_x was generated with 6 to 7 percent oxygen levels. At higher excess oxygen levels, thermal NO_x formation was suppressed because of the cooling of the peak flame temperature.

Firing the furnace at extremely high or low excess-air levels created other effects on furnace performance besides reducing NO_x formation. Firing at extremely low levels of excess air can lead to flame instability and incomplete combustion. If the control is adequate, low excess-air firing enhances furnace efficiency by limiting the amount of inerts being passed through the system. Firing at extremely high levels of excess air leads to flame instability and decreases in furnace efficiencies. Approximately 10 percent excess air represents the typical heater operation.

Flue gas recirculation involves recirculating a portion of the inert combustion products into the combustion chamber. This can be done either internally or externally. Recirculating the inert combustion by-products dilutes the combustion reactants, reducing the peak flame temperature and partial pressure of available oxygen at the burner. Reducing the peak flame temperature retards thermal NO_x formation, and reducing the amount of oxygen available limits both thermal and fuel NO_x formation.

Table 5-7 shows the effect of flue gas recirculation on NO_x formation at various levels of combustion air preheat. Figure 5-7 shows that the effect of high temperature combustion air on NO_x formation is reduced at higher levels of flue gas recirculation. Combustion air temperature and recirculation, however, have opposite effects on furnace efficiency. Increasing the combustion air temperature increases furnace efficiency; whereas, increasing the rate of recirculation decreases furnace efficiency. Increasing combustion air temperature enhances radiation heat transfer, while increasing recirculation reduces radiation heat transfer.

TABLE 5-7. EFFECT OF FLUE GAS RECIRCULATION (FGR) ON NO_X EMISSIONS

Combustion Air Temperature (°F)	FGR %	NO_x, ppm, corrected to 0% excess air.	NO_x lbs/10^6 Btu
803	5	229	.232
814	10	180	.183
813	10	180	.183
830	20	86	.085
1003	5	350	.355
1004	5	350	.355
992	20	143	.145
991	20	143	.145
1199	5	428	.434
1178	10	333	.338
1172	20	178	.180
1172	20	178	.180

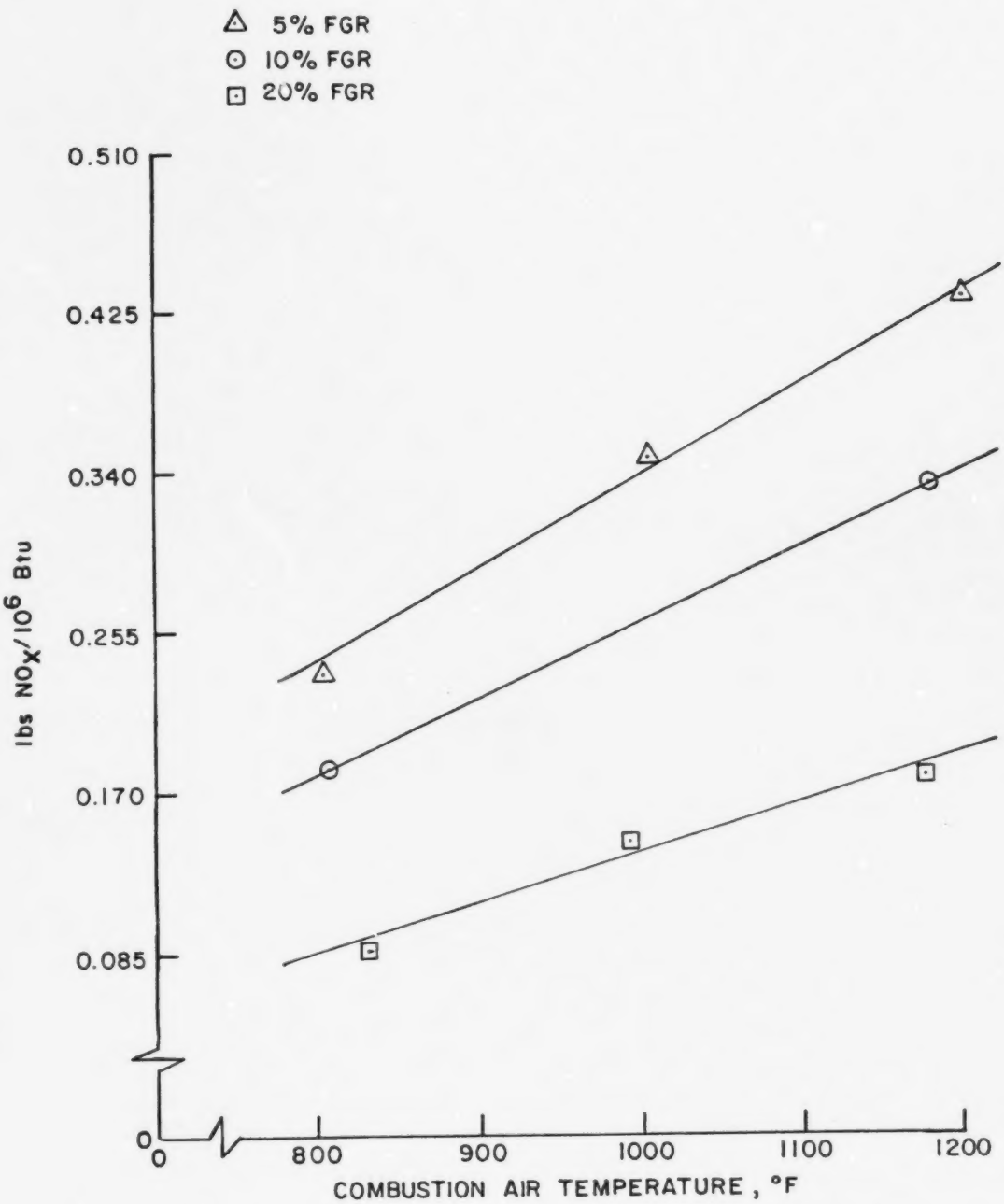

Figure 5-7. Effect of flue gas recirculation on combustion air temperature and NO_x emission factor relationship.

Glass Melter Ports

Many industrial heating processes, such as glass melters and cement kilns, can operate with combustion air temperatures higher than the metals industries. Emission tests were conducted for combustion air temperatures of 1600°F to 2200°F from a glass melter port on a pilot-scale furnace. The effects of stoichiometric ratio (fuel rich to 8 percent excess oxygen), fuel injection velocity (67 to 190 ft/sec), firing rate (2.2 to 3.0 million Btu/hr), and flue gas recirculation (5 and 10 percent) on NO_x formation were investigated.

The following conculsions can be drawn from the results of these tests:

- Burner design is indeed a significant parameter affecting NO_x formation. Although the furnace temperatures were higher during tests on the glass melter port, the NO_x emissions were lower than values that would have been predicted by extrapolating data from the baffle burner.
- Low excess air firing was effective in reducing NO_x emissions.
- Combustion air temperatures significantly affect NO_x emissions.
- Flue gas recirculation and reduced firing rate were not effective in reducing NO_x emissions.

Tables 5-8, 5-9, and 5-10 show the effect of excess oxygen on NO_x formation in the furnace set-up tested at various combustion air temperatures. At each air temperature studied, NO_x formation increased with excess oxygen levels up to between 6 and 7 percent O_2. At all excess oxygen levels tested, the NO_x emissions increased with combustion air temperature. Figures 5-8, 5-9, and 5-10 show the linear trend of increasing NO_x formation with increasing excess oxygen.

In general, at all stoichiometric ratios, increasing the combustion air temperature by 200°F increased the NO_x emissions by 45 to 50 percent, and at all combustion air temperatures, increasing the excess oxygen from 2 to 4 percent increased the NO_x emissions by approximately 20 percent. In comparison to data taken during tests of the Bloom hot air baffle burner, NO_x emissions from the glass melting furnace were shown to be less sensitive to both the combustion air temperature and the levels of excess oxygen.

TABLE 5-8

220°F Air, 3×10^6 Btu/hr, 3/4 inch nozzles

O_2 (excess)	NO_x (lbs/10^6 Btu)
7.6	4.115
6.1	4.257
5.0	4.042
4.0	3.458
3.2	3.211
1.9	2.713
1.0	2.355
0	1.573

TABLE 5-9

1800°F Air, 3 x 10^6 Btu/hr, 3/4 inch nozzles

O_2 (excess)	NO_x (lbs/10^6 Btu)
8.0	1.910
6.9	1.954
6.2	1.948
5.3	1.850
3.8	1.712
2.1	1.639
2.2	1.367
1.0	1.178
0	0.909

TABLE 5-10

1500°F Air, 3 x 10^6 Btu/hr, 3/4 inch nozzles

O_2 (excess)	NO_x (lbs/10^6 Btu)
7.8	1.263
7.0	1.343
6.1	1.347
5.2	1.371
4.1	1.174
3.1	1.060
2.1	0.942
1.0	0.810
0	0.558

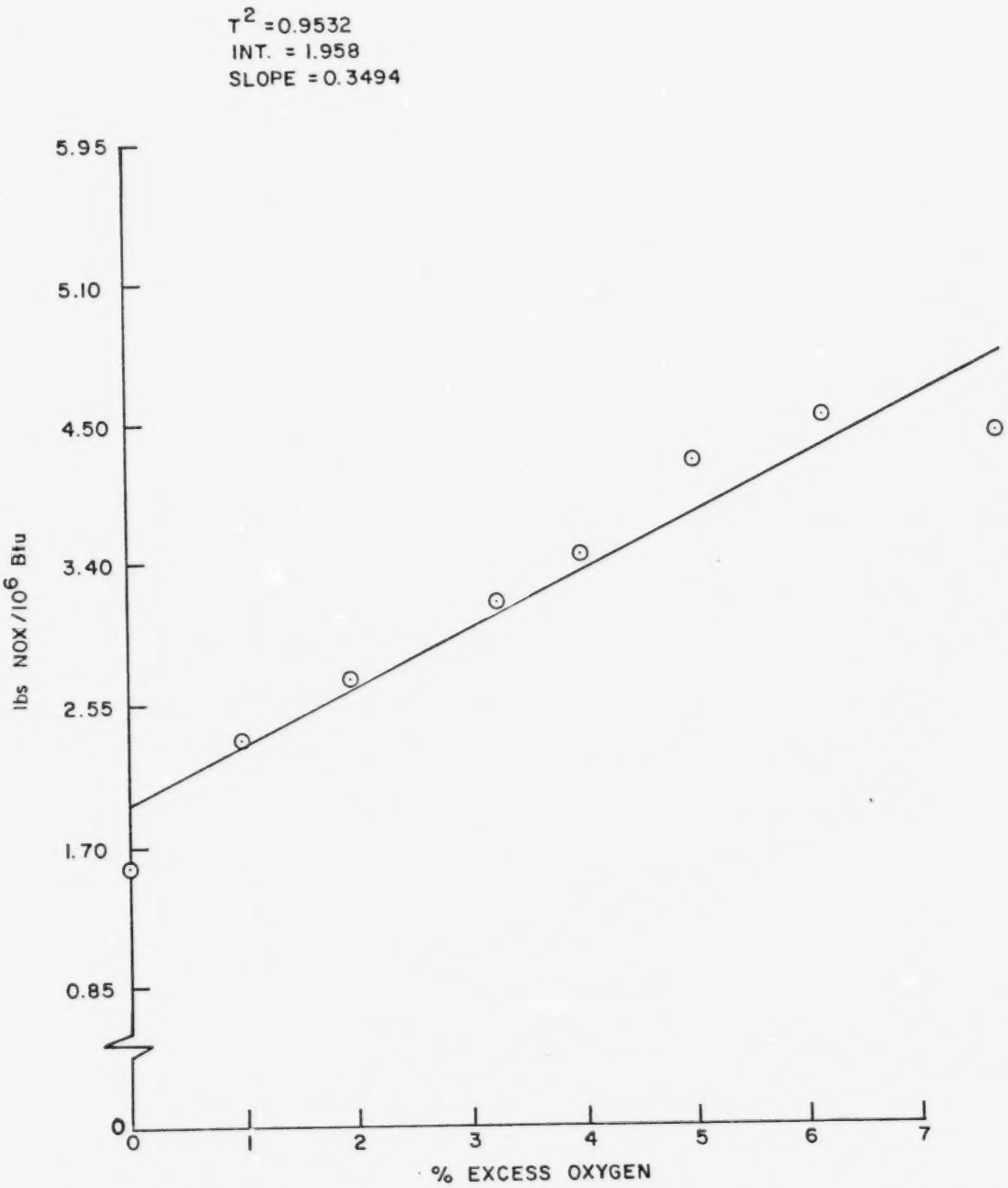

Figure 5-8. Effect of excess oxygen on NO_x emission factor for glass melter port with 2200°F combustion air, 3 x 10^6 Btu/hr, 3/4 inch nozzles.

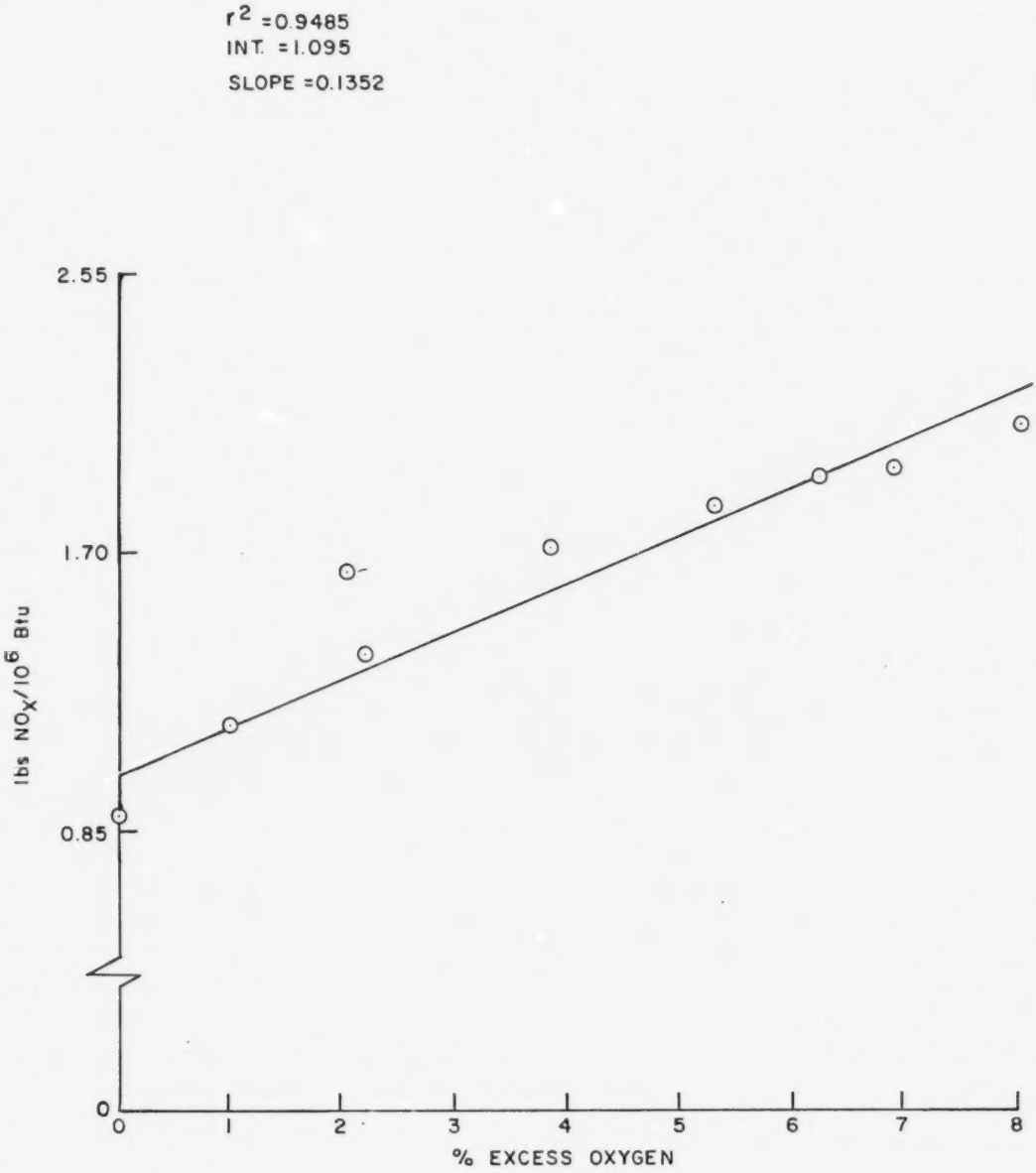

Figure 5-9. Effect of excess oxygen on NO_x emission factor for glass melter port with 1800°F combustion air, 3 x 10^6 Btu/hr, 3/4 inch nozzles.

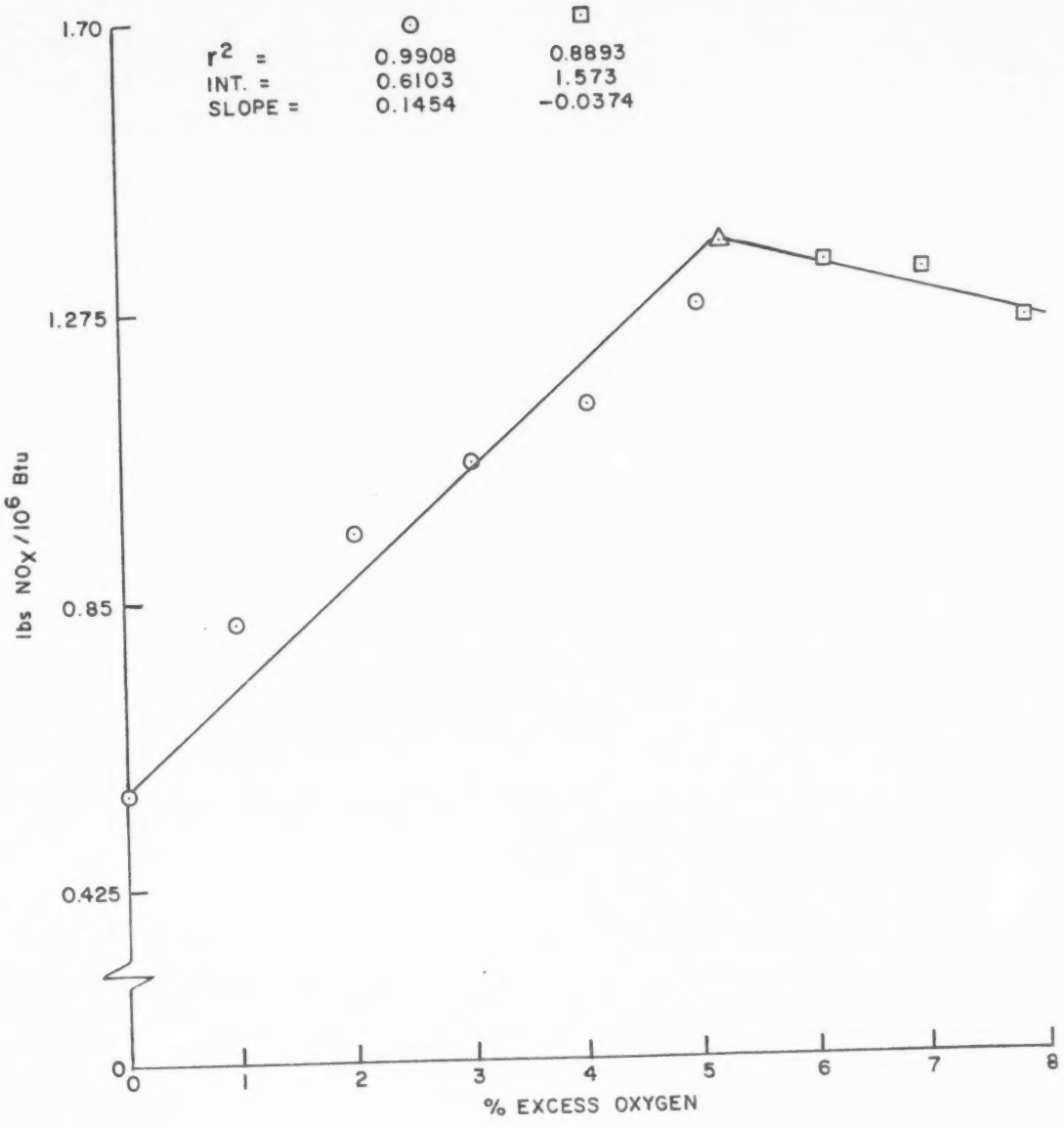

Figure 5-10. Effect of excess oxygen on NO_x emission factor for glass melter port with 1600°F combustion air, 3 x 10^6 Btu/hr, 3/4 inch nozzles.

This diminished sensitivity indicates the effects of burner design on NO_x emissions. Due to the burner, the flames in the glass furnace would be less turbulent than those in the soaking pit, resulting in less opportunity for the nitrogen-oxygen reaction to occur. Correspondingly, measurements of flame length in the glass furnace remained virtually constant at each level of excess air throughout the range of combustion air temperatures. The flame length increased significantly with decreases in excess air at all combustion air temperatures.

Because of the larger combustion zones present in the glass furnace and in furnaces of similar designs, the effect of furnace temperature was investigated. The results of these tests indicate the effects of heat removal by the furnace from the large combustion zone on NO_x formation. Figures 5-11, 5-12, and 5-13 show that at excess oxygen levels close to stoichiometric, the furnace temperatures do not have any significant effect on NO_x emissions; however, with excess oxygen the NO_x emissions increased with increasing roof temperature. The rear roof temperature was selected for measurement because it was closest to the bridgewall of the furnace.

Although fuel injection velocities were shown by IGT to affect NO_x formation, these are not addressed here; rather, fuel velocities corresponding to the typical velocities achieved using a 3/4-inch nozzle are used consistently in the analysis.

Externally recirculating flue gases into the combustion zone would reduce NO_x formation by reducing peak flame temperatures and by reducing the combustion zone oxygen concentrations by dilution. During the IGT tests of the Bloom hot air baffle burner, flue gas recirculation was effective in reducing NO_x formation, especially at high combustion air temperatures. Because the combustion air temperatures in the glass melting furnace were much higher, a more dramatic effect on NO_x formation by flue-gas recirculation was expected. The types of flames present in the baffle burner and the glass melting furnace differ significantly. Long, lazy flames would be more common in glass melter parts. Flue gas recirculation was not effective in reducing NO_x emissions from the melting port at the firing conditions tested.

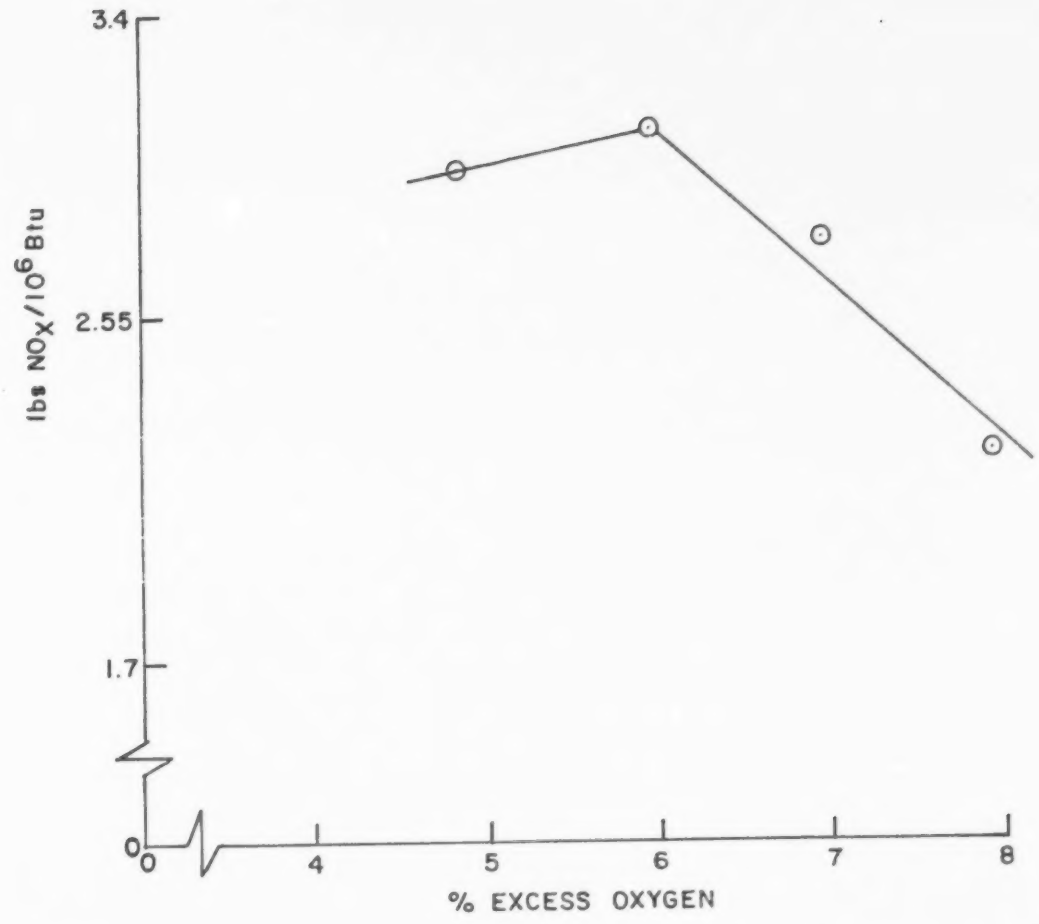

Figure 5-11. Effect of excess oxygen on NO_x emission factor for glass melter port with 2000°F combustion air 3 x 10^6 Btu/hr, 3/4 inch nozzles, 2600°F rear roof temperature.

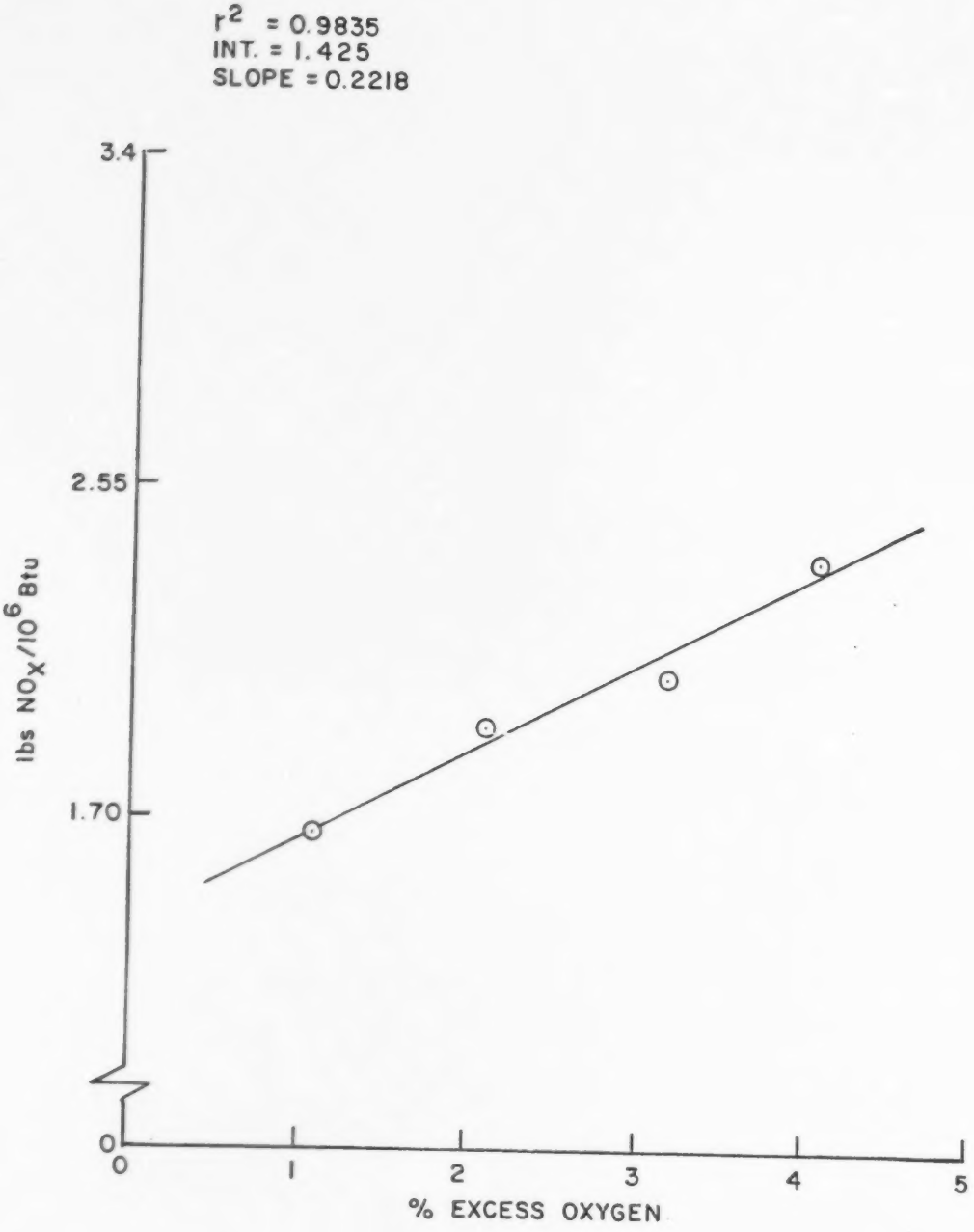

Figure 5-12. Effect of excess air on NO_x emission factor for glass melter port with 2000°F combustion air, 3×10^6 Btu/hr, 3/4 inch nozzles, 2545°F rear roof temperature

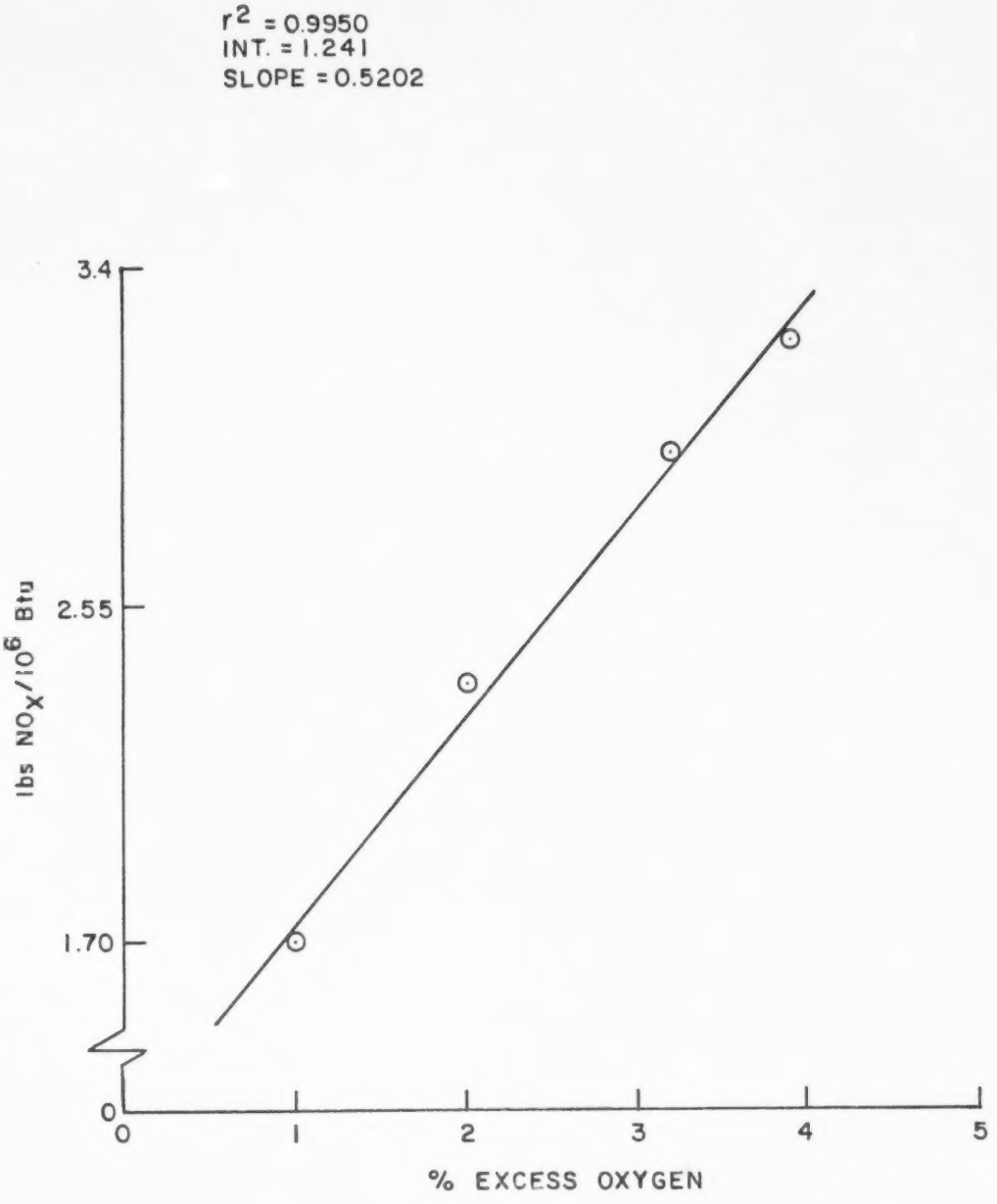

Figure 5-13. Effect of excess oxygen on No_x emission factor for glass melter port with 2000°F combustion air, 3 x 10^6 Btu/hr 3/4 inch nozzles, 2690°F rear roof temperature.

Since flue gas recirculation was not very effective in reducing NO_x formation, Figure 5-14 summarizes the overall results of the glass melting port relevant to the goals of this study.

LOW-NO_x BURNERS

As described above, the increasing use of recuperators and regenerators for energy conservation in process heating applications in the steel, aluminum, glass industries, and other similar applications can result in increased NO_x emissions due to the effect of air preheat on flame temperatures. A great deal of research has been directed toward lower NO_x emissions from large utility boilers, which are the largest stationary sources of these emissions. Some of this research is applicable to the development of low-NO_x industrial burners; however, each industrial burner must incorporate NO_x control techniques while still maintaining heat transfer characteristics of the flames that are suitable for the industrial process to which it is applied.

IGT under the direction of the Gas Research Institute (GRI) has performed research involving multifuel low-NO_x burners.[11] The objective of this program was to develop low-NO_x burners capable of operating with relatively high (1200°F) air preheat temperatures. The goal of one task was to develop a medium-velocity low-NO_x burner that has a high convective heat trasfer for direct-fired applications in aluminum reheating and melting furnaces. The goal of a second task was to develop a low-NO_x baffle burner for direct-fired furnaces in the steel, aluminum, and glass industries.

In the development of a low-NO_x burner for aluminum reheat and melting furnaces, IGT and GRI used a Hauck Hot Air Enerjet Series High Velocity Combination Burner (Model EJC-H, Figure 5-15) for baseline results. Prototype development focused along the lines of two stage recirculating type burner.

During testing, IGT concluded that two models designated 2B and 3B (shown in Figures 5-16 and 5-17 showed promise for future commercial use. Table 5-11 and Figures 5-18 and 5-19 summarize the results of these

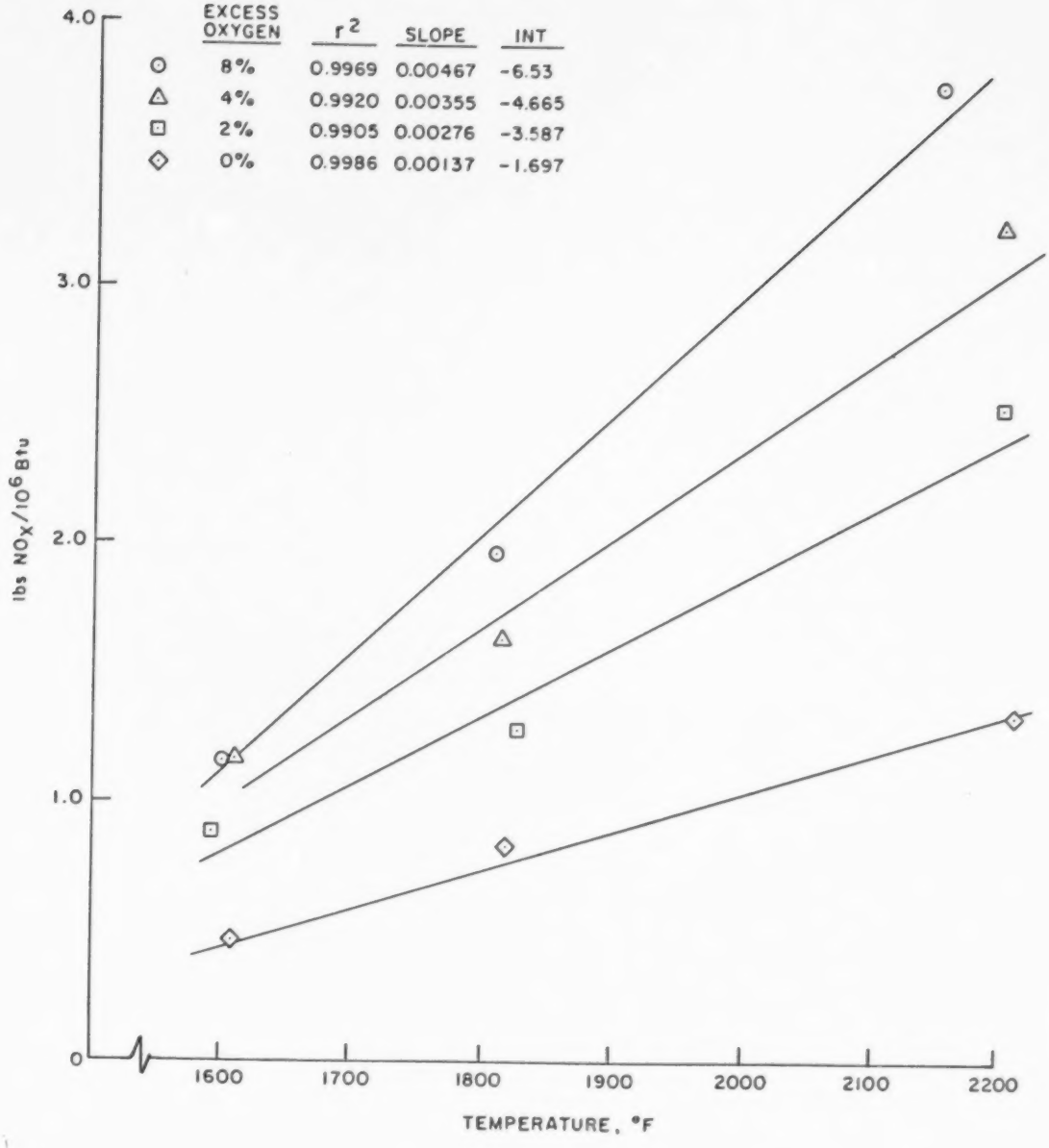

Figure 5-14. Effect of combustion air temperature on NO_x emission factors at various levels of excess oxygen.

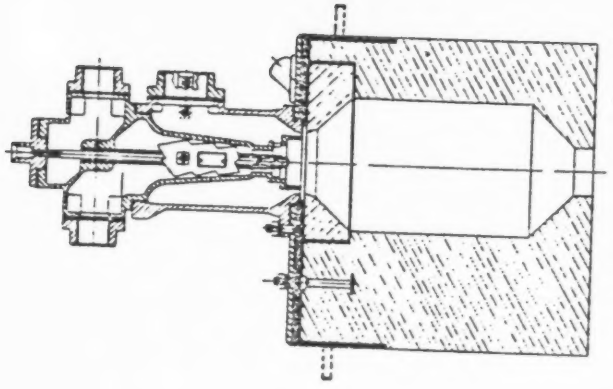

Figure 5-15. Typical EJC Burner Cross Section
Source: Reference 11

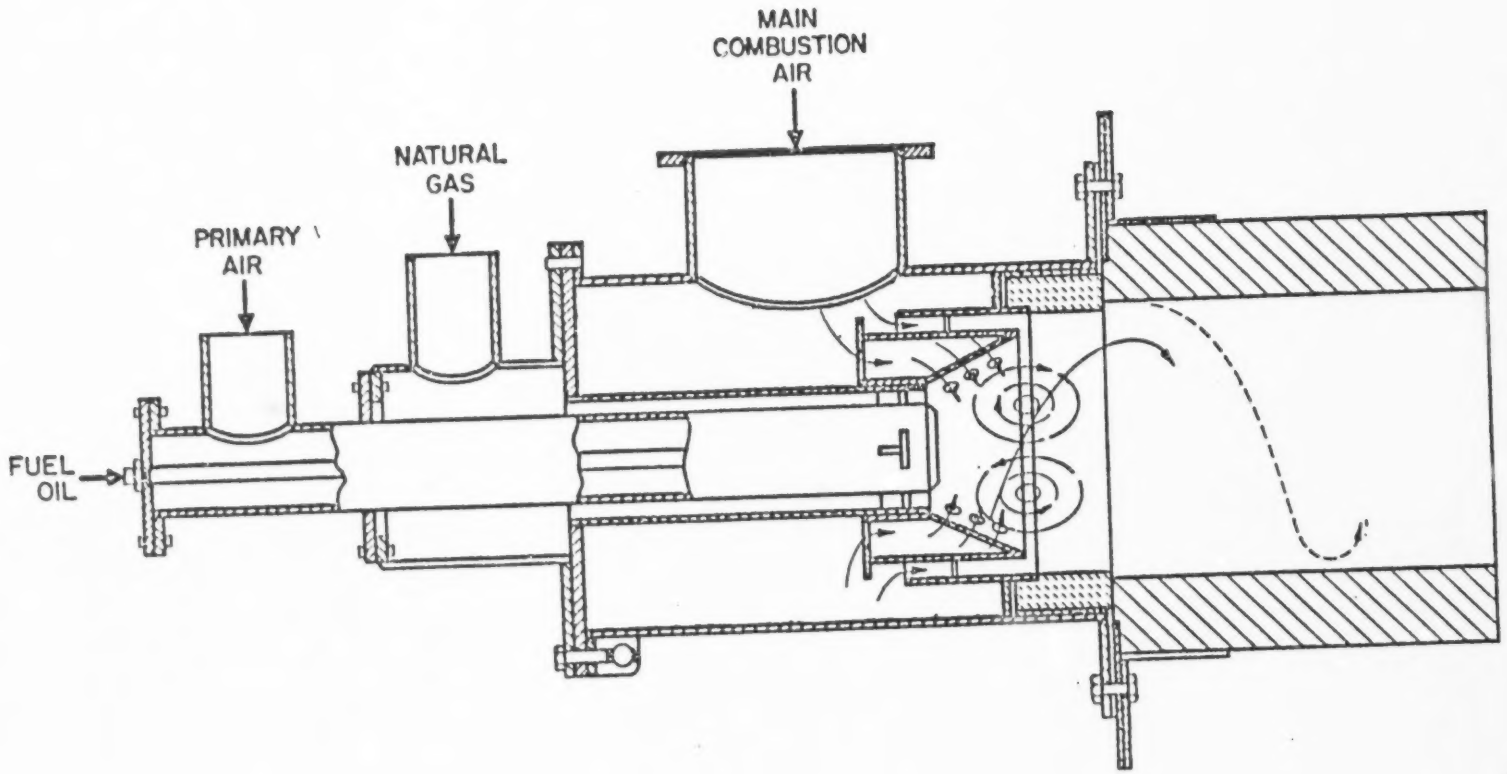

Figure 5-16. Prototype Burner 2B
Source: Reference 11

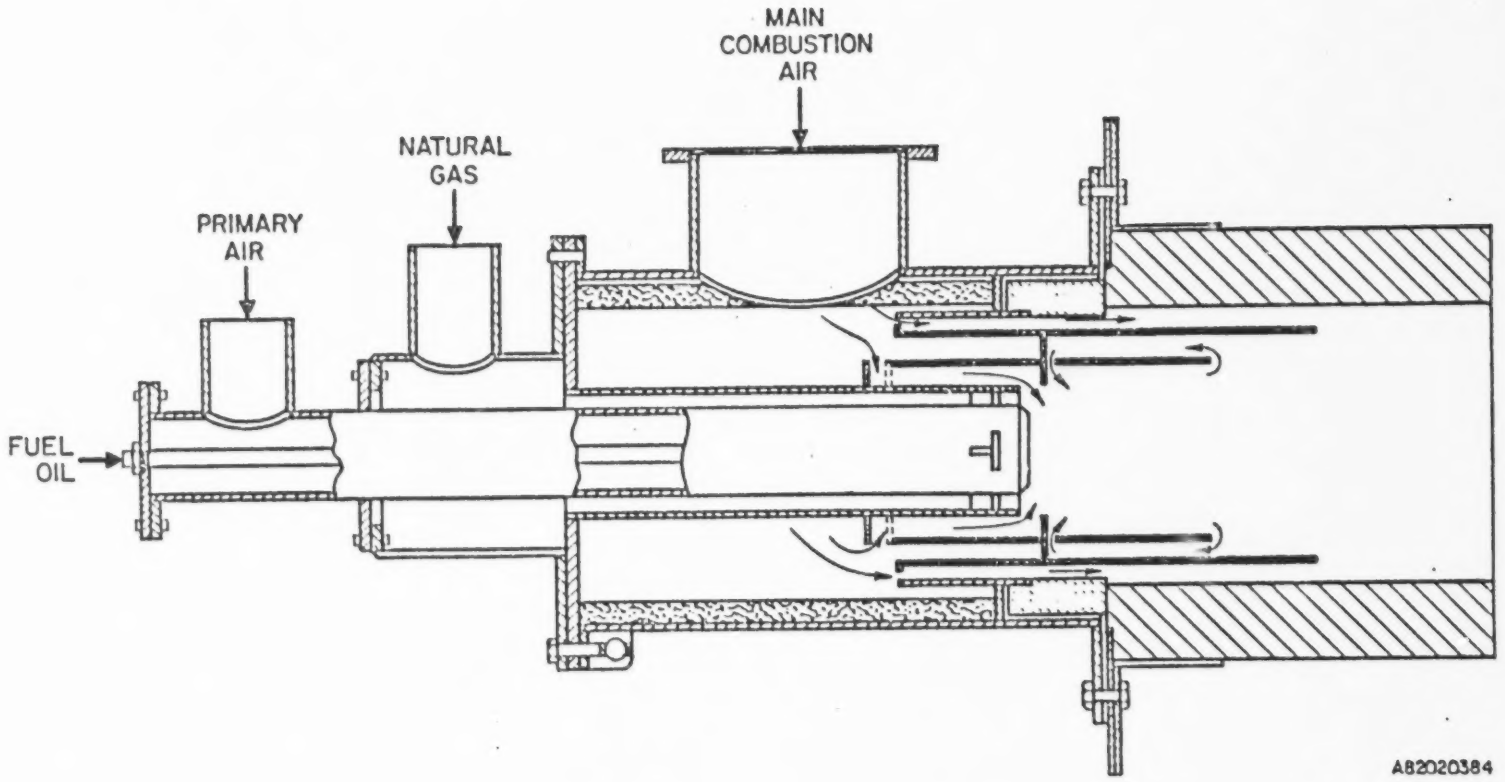

Figure 5-17. Prototype Burner 3B
Source: Reference 11

TABLE 5-11. Summary of Baseline and Prototype Burners

2B and 3B Data

Burner	Firing Rate x 10^{-6} BTU/hr	Primary Air Flow SCF/min	Excess Air (%)	Combustion Air Temperature (°F)	Flame Length (ft)	No_x lbs/10^6 BTU Corrected to 0% O_2
Baseline	3.8	2200	5	140	3.9	.070
2B	3.8	1000	5	110	6.6	.0558
3B	3.8	1000	5	130	7.9	.0466
Baseline	3.0	2200	5	135	--	.070
Baseline	3.0	0	5	135	--	.070
2B	3.8	0	5	110	--	.061
3B	3.8	0	5	130	--	.0466
Baseline	2.0	2200	6	140	--	.0923
2B	2.0	1000	5	110	--	.0558
3B	2.0	1000	5.5	130	--	.0518
Baseline	3.0	2200	5	825	2.3	.2030
2B	3.0	1000	5	800	5.0	.162
3B	3.0	2200	5.5	820	4.3	.152
Baseline	2.6	0	5	850	--	.228
Baseline	2.6	0	5	800	--	.311
2B	3.0	0	5	800	--	.182
3B	3.0	0	5.5	820	--	.152

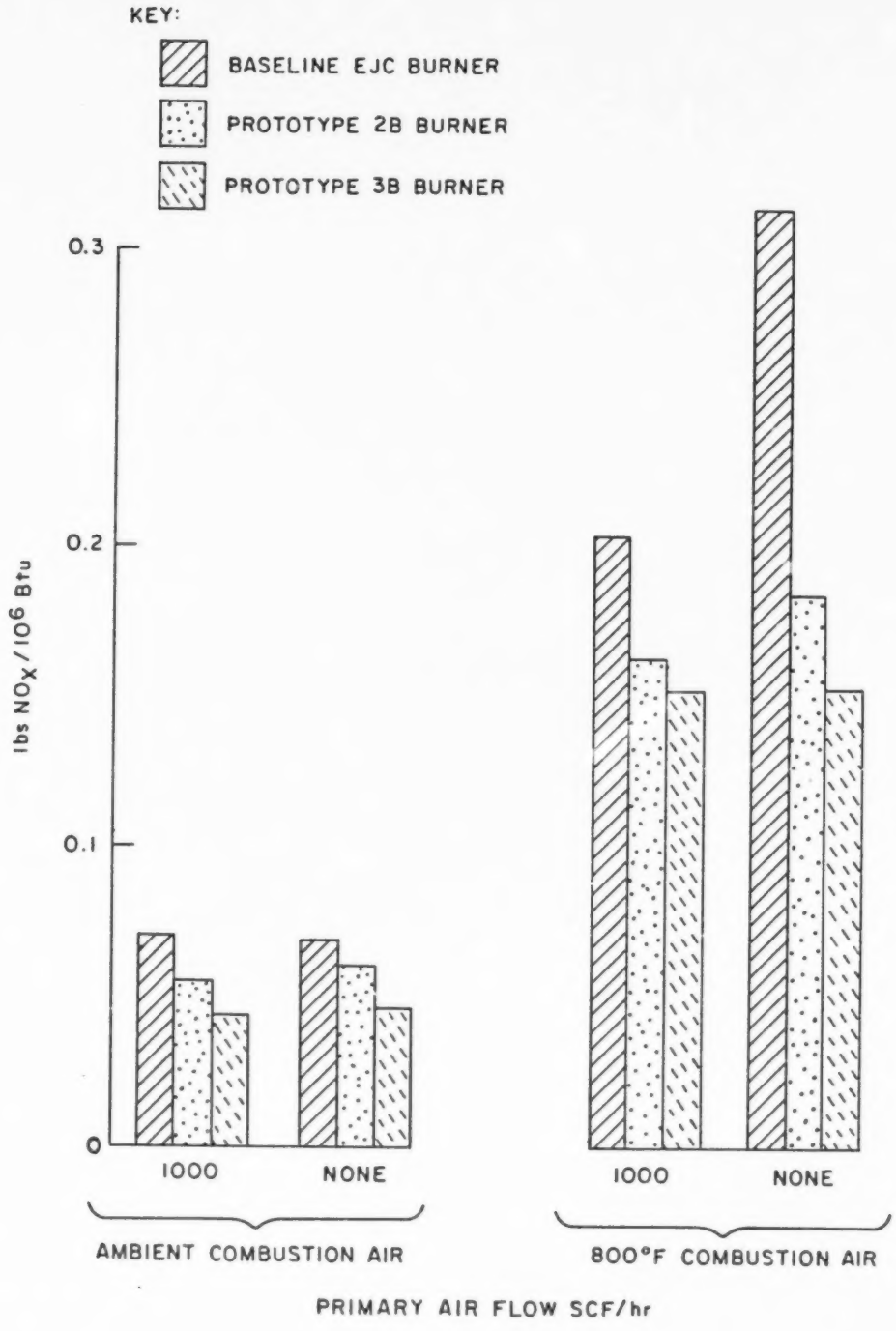

Figure 5-18. Comparison of NO_x Emission factors of baseline and prototype burners.

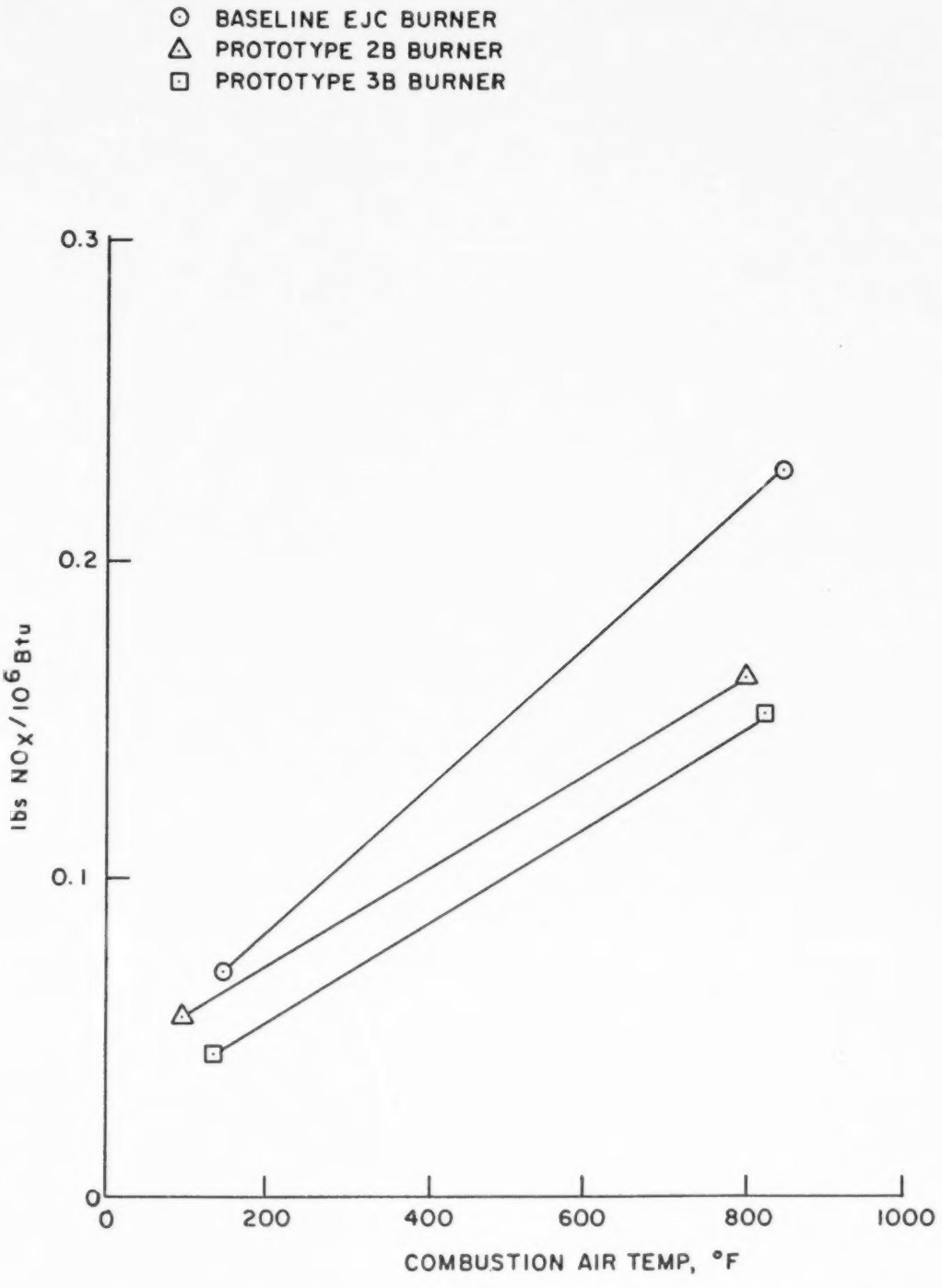

Figure 5-19. Effect of combustion air temperature on No_x emission factors for baseline and prototype burners.

tests. With no primary air and 800°F combustion air, NO_x emissions for burners 2B and 3B were 40% and 50% lower, respectively, compared to the baseline, between 10 and 40 percent lower for 2B, and 25 to 45 percent lower for 3B, depending on firing conditions.

The flame for both prototype burners was longer than that of the baseline burner. This was expected since the baseline was a high velocity burner (30,000 ft./min.) as opposed to the prototypes which were medium high velocity burners (15,000 ft./min.). The flame lengths were judged acceptable for both prototype burners.

In general, IGT concluded that prototype 2B should be a good candidate for industry operations using high (800°F) combustion air preheat temperatures. Burner 3B was judged to be a good candidate for a wide variety of industrial applications, due to it ability to perform well under a variety of operating conditions. In addition, IGT concluded that additional research needs to be performed particularly with respect to oil firing. IGT stressed that the prototype burners are not yet optimized and future performance increases should be expected with further funding.

The goal of the second task was to develop prototype low-NO_x burners for use in the steel, aluminum, and glass industries. IGT and GRI with Bloom Engineering both developed these prototypes, and tested them against a Bloom baseline burner (model 1201-100 FTR gas, 1821-030 FET retractable oil burner, Figure 5-20). Both natural gas and No. 6 heavy oil were to be used as fuel.

Bloom Engineering prepared the outline of the testing procedure. The tests focused on obtaining a battery of data for conditions at:

1) 750°F air preheat, natural gas first, oil utilizing steam atomization second; and

2) 1200°F air preheat, again natural gas first and oil utilizing steam atomization second.

These conditions were used to gather a series of data for both the baseline burner, and a prototype developed by Bloom (Figure 5-21). Bloom Engineering did design and fabricate two new baffles for the prototype, since the original baffle produced unsatisfactory flame characteristics. Screening tests enabled IGT to select a baffle design that had acceptable characteristics (12 tertiary air holes and spin and convergence).

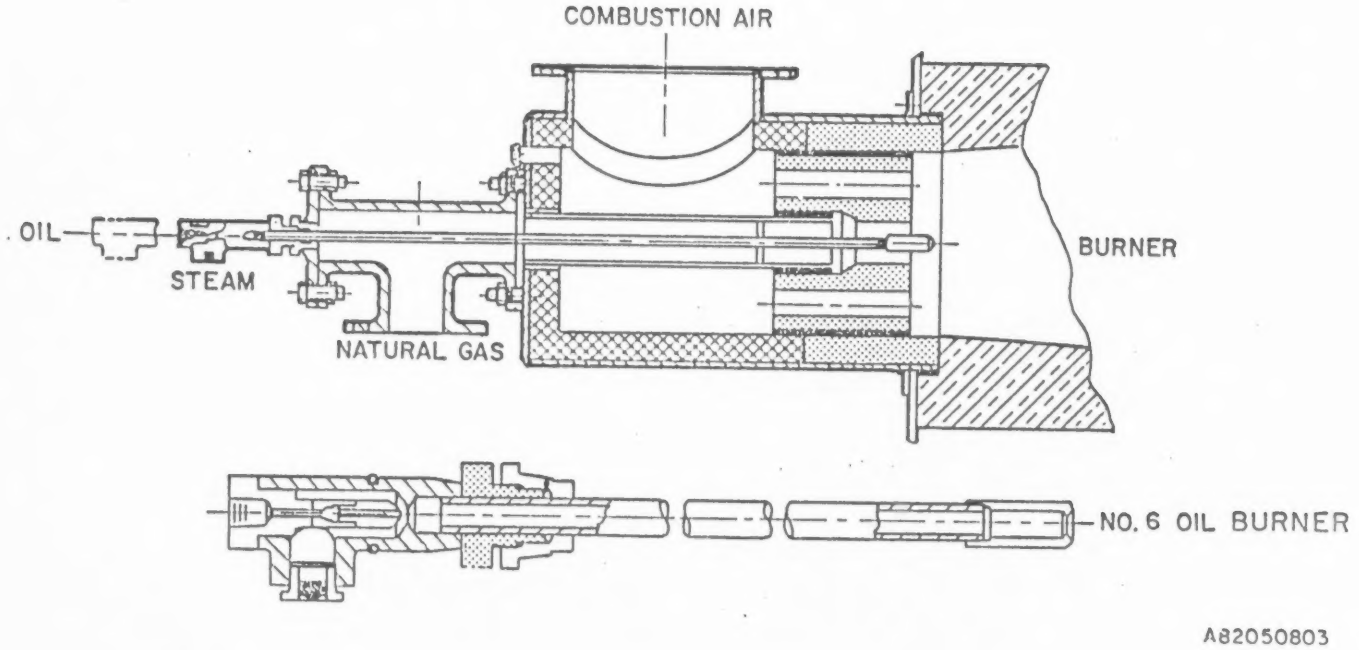

Figure 5-20. Cross Section of Standard Burner
Source: Reference 11

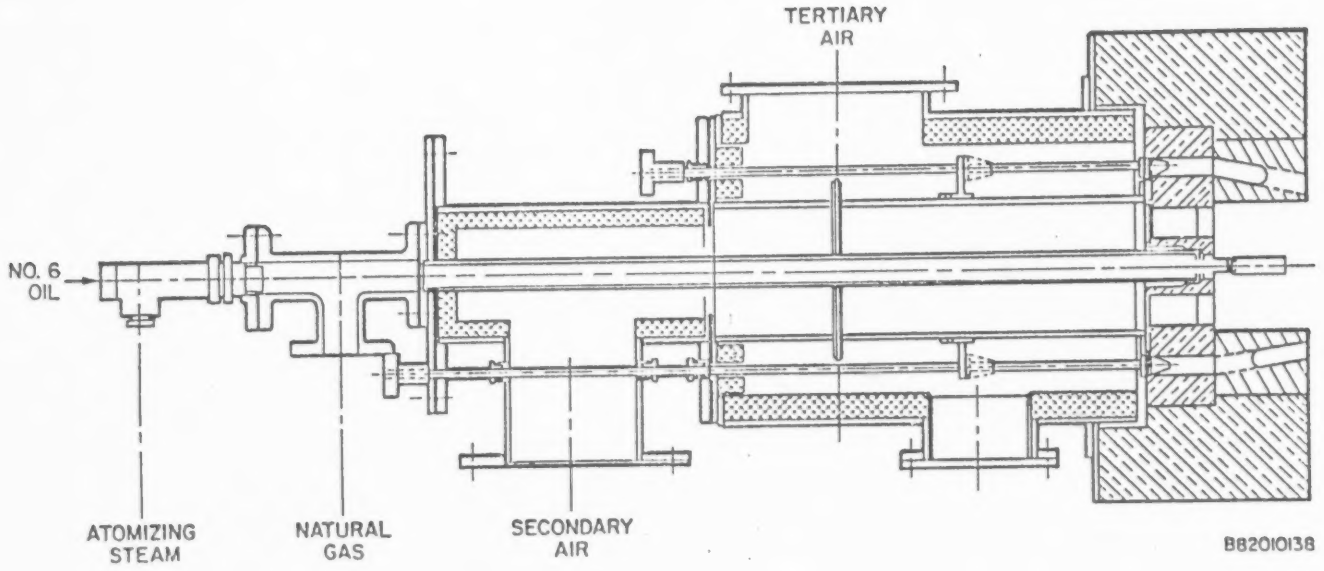

Figure 5-21. Cross Section of Prototype Low-NO_x Burner
Source: Reference 11

Table 5-12 shows a direct comparison between the standard and prototype burners for a variety of operating conditions. For gas firing, NO_x emission reductions ranged from 46 percent (2×10^6 Btu/hr., 800°F combustion air) to 56 percent (2×10^6 Btu/hr., 1100°F combustion air).

Figure 5-22 compares the effect of preheated combustion air on NO_x emissions. The figure shows the prototype burner as considerably less sensitive to preheat temperatures. A 400°F increase in air preheat temperature (700-1100°F) increased NO_x emission by 148 percent, while this same increase for the prototype burner increased emissions by only 75 percent.

Figure 5-23 illustrates similar relationships for excess oxygen levels, with the prototype having significantly less sensitivity to excess oxygen levels. For example, a 2 percent increase (1 to 3 percent) in the oxygen level gave a 60 percent emission increase for the baseline burner, while the prototype increase was only 38 percent. Hence, from a NO_x emission standpoint, excess air level control is much less critical for the prototype.

SUMMARY

The design parameters and operating conditions of direct-fired process heaters determine, to a large extent, the temperature, turbulence, and reaction time of air and fuel in the combustion zone. Both theoretical studies and results of emission testing programs indicate that these factors affect formation of NO in the combustion zone. Combustion air preheat, which affects flame temperature, reactant turbulence, and residence time, has been shown to impact significantly NO_x emissions from the two broad distinct classifications of industrial direct-fired process heaters. Theoretical studies also suggest that combustion air preheat should affect NO formation rates.

Table 5-13 presents the NO_x emission factors at various levels of combustion air preheat for two furnaces representing the broad classifications of direct-fired heaters used in energy-intensive industries, for a theoretically-based model furnace, and for prototype low-NO_x burners capable of industrial use. These results can be used to develop NO_x emission factors for the range of process heaters used in energy-intensive industries.

TABLE 5-12. Summary of Standard and Prototype Low-NO_x Burner Data

	Burner	Conditions: Total Heat Input 10^6 BTU/hr	Conditions: Combustion Air Temp. (^oF)	Measurements: Excess Air %	Measurements: Flame Length cm	Measurements: Efficiency %	Measurements: Flue Gas ^oF	Measurements: O_2 %	Measurements: NO_x lbs/10^6 BTU	Measurements: % Change
GAS	Standard	4.0	1100	10	190	44	2430	1.9	.568	
	Prototype	4.0	1135	10	170	44	2360	2.2	.264	53
	Standard	4.0	740	9	245	40	2400	1.8	.294	
	Prototype	4.0	780	10	190	39	2400	2.0	.152	48
	Standard	2.0	1085	14	155	36	2080	2.9	.467	
	Prototype	2.0	1105	10	155	42	--	1.9	.203	56
	Standard	2.0	740	12	190	35	2160	2.5	.254	
	Prototype	2.0	790	10	165	36	2230	2.2	.137	46
OIL	Standard	4.1	1100	10	210	39	2580	1.9	.233	
	Prototype	4.0	1080	10	160	40	2460	1.9	.345	-48
	Standard	4.1	740	10	220	--	2500	2.0	.254	
	Prototype	4.1	800	10	190	--	--	2.0	.268	-6

NO_x data corrected to 0% O_2

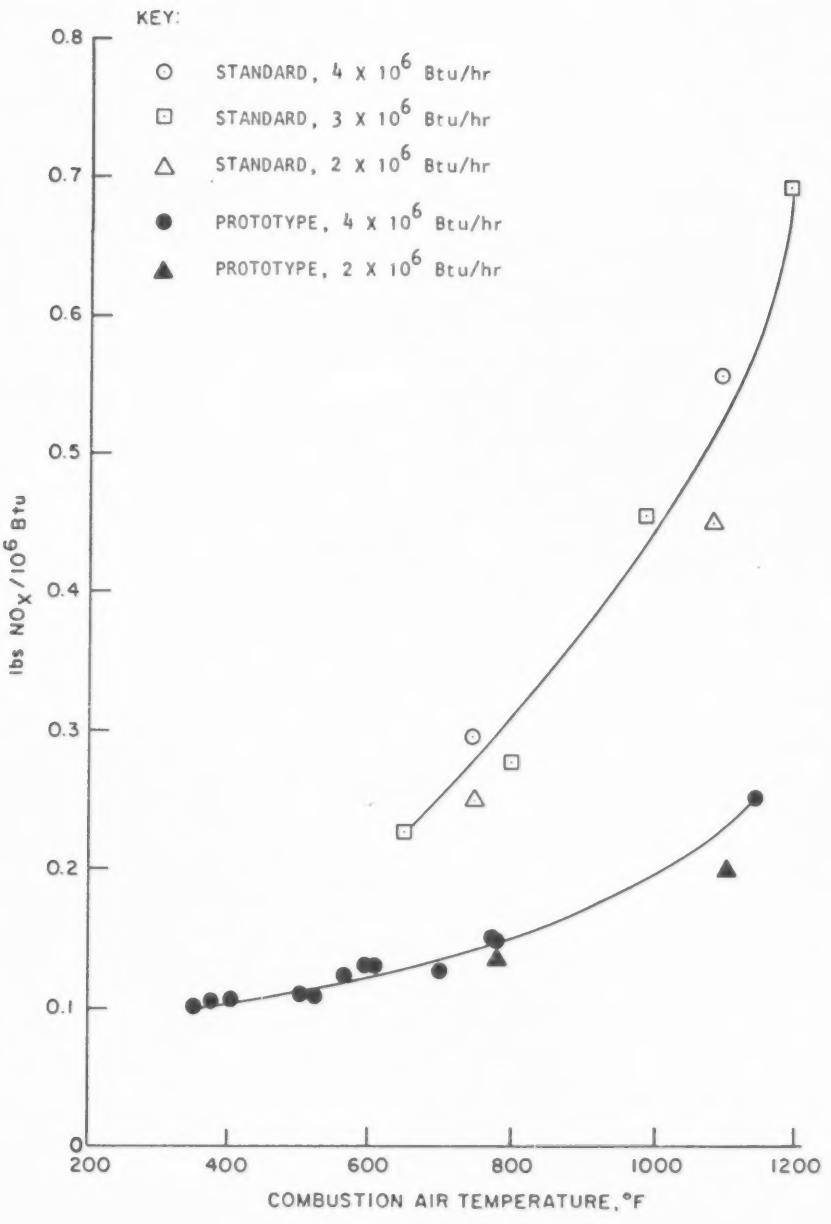

Figure 5-22. Effect of combustion air temperature on No_x emission factors for standard and prototype burners.

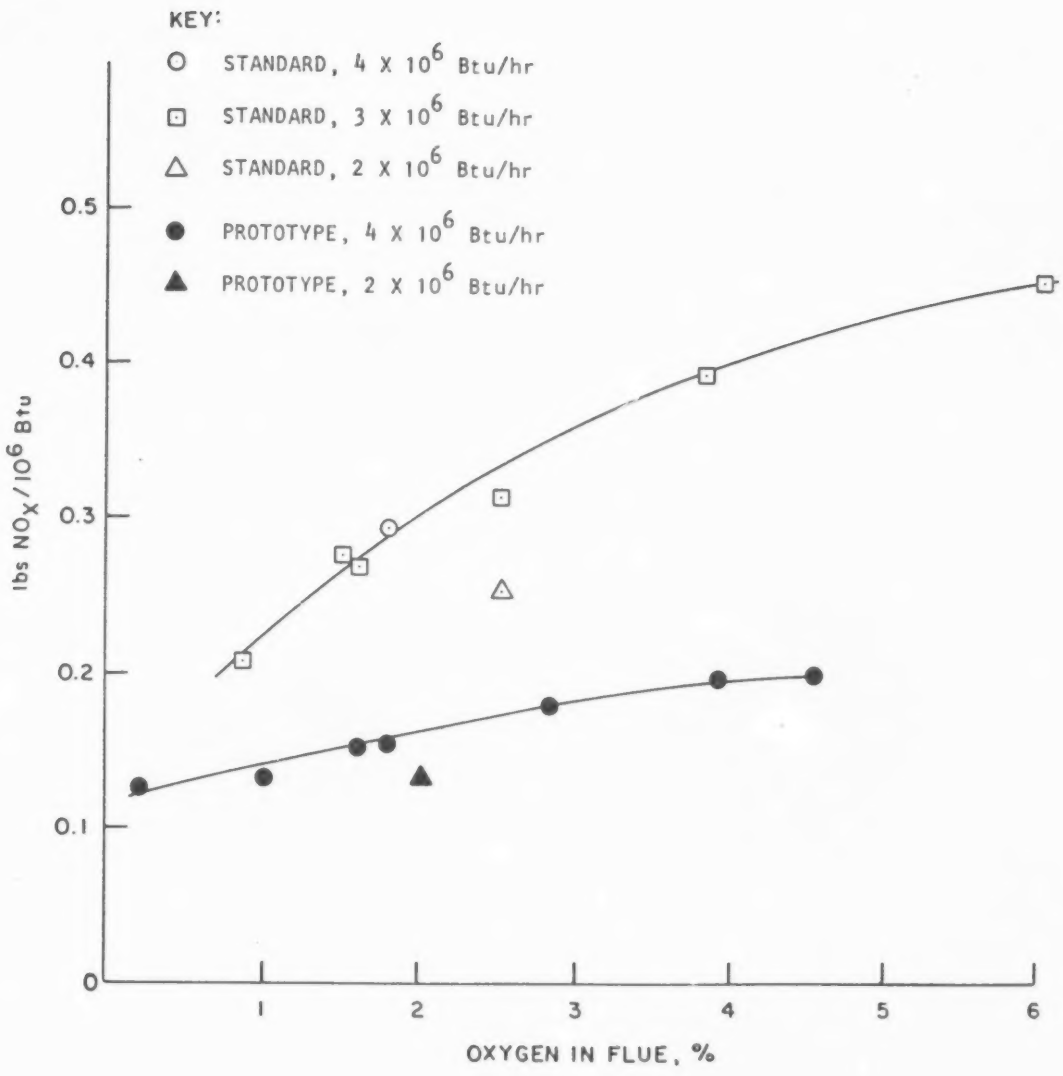

Figure 5-23. Effect of excess oxygen on No_x Emission factors for standard and prototype burners.

Table 5-13. Study Summary of NO_x Emission Factors

Combustion Air Temperature (°F)	NO_x Emission factors ($lbs/10^6$ Btu) Theoretical	Steel Industry Baffle Burner	Glass Industry Burner	Low-NO_x Prototype Burner
800	0.01	0.34	--	0.15
1000	0.20	.48	--	0.19
1200	0.34	0.72	--	0.28
1400	0.62	--	--	--
1600	1.12	--	0.80	--
1800	1.77	--	1.30	--
2000	2.92	--	1.80	--
2200	--	--	2.45	--

SECTION 6
EMISSION FACTOR DEVELOPMENT

Based on the analysis of furnace designs and operating conditions, two broad categories of furnaces or heaters have been identified. For these two categories, quantitative trends of increasing NO_x formation with increasing combustion air temperature have been established. These trends in NO_x for formation make no distinction between various members of the categories of heaters.

Without a representative sample of existing industrial-sized heaters over a complete range of combustion air temperatures, and fuels emission factors can be considered only estimates of trends. The test programs described in this report were limited to heaters with design and operating conditions representative of steel industry process heaters and glass melting furnaces burning natural gas. Based on similarities of design and operating conditions, data from these studies were able to be transferred to other heater designs and fuels. Prior to this analysis, NO_x emission factors determined for industrial boilers were applied to all enclosed combustion devices, including direct-fired process heaters.

ENVIRONMENTAL RESULTS

Nitrogen oxides emission factors for process heaters in energy-intensive industries can be described by Figure 6-1 for steel reheat, steel soaking pit, aluminum reheat, aluminum melting, steel forging, annealing, refinery process and titanium and nickel melting furnaces and by Figure 6-2 for glass melting furnaces and cement kilns. These figures represent NO_x emission trends for these furnaces under typical operating conditions.

The following factors should be considered when applying these factors in estimating total NO_x emission from the process heaters and direct-fired furnaces:

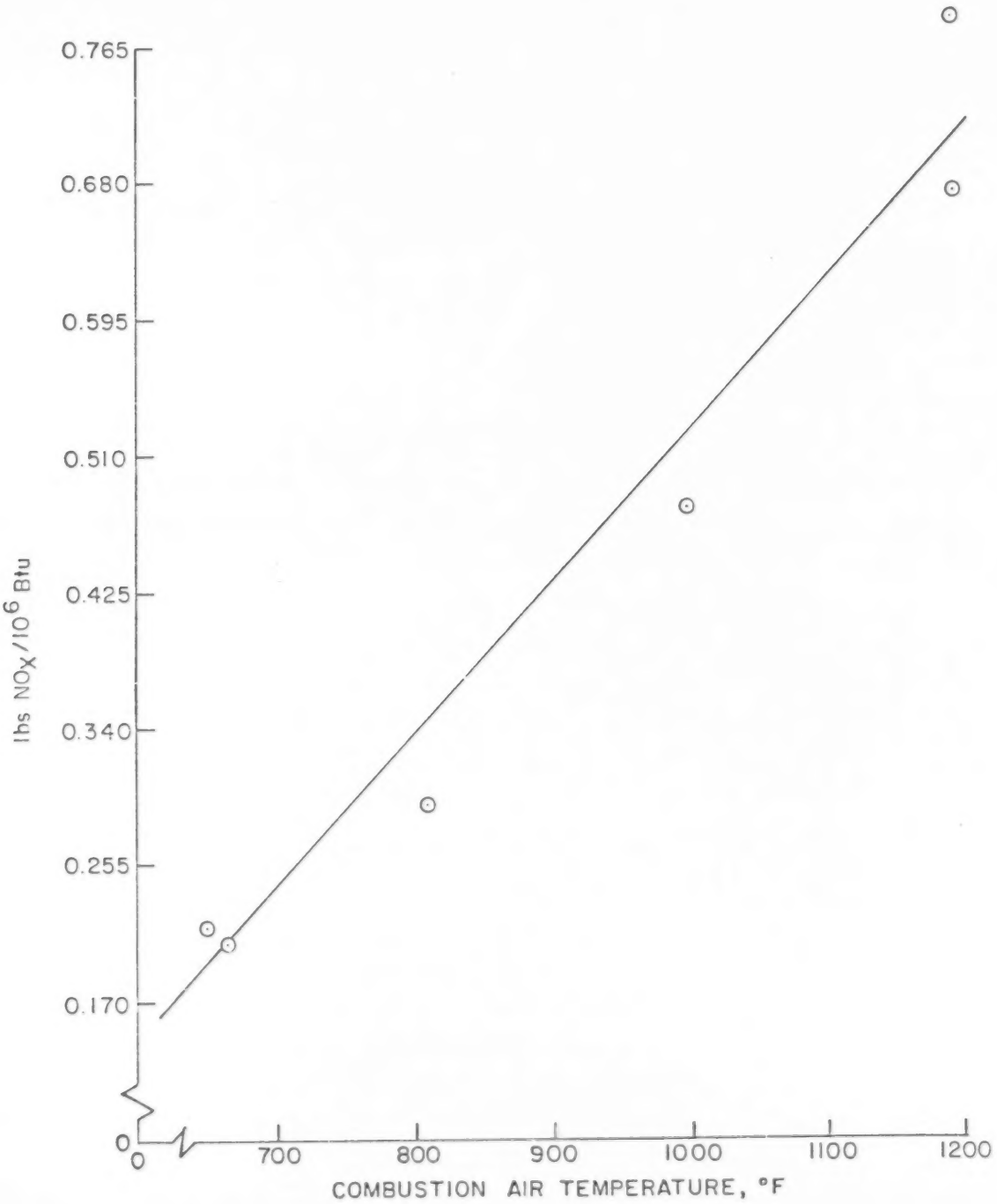

Figure 6-1. Relationship between No_x emission factor and combustion air temperature.

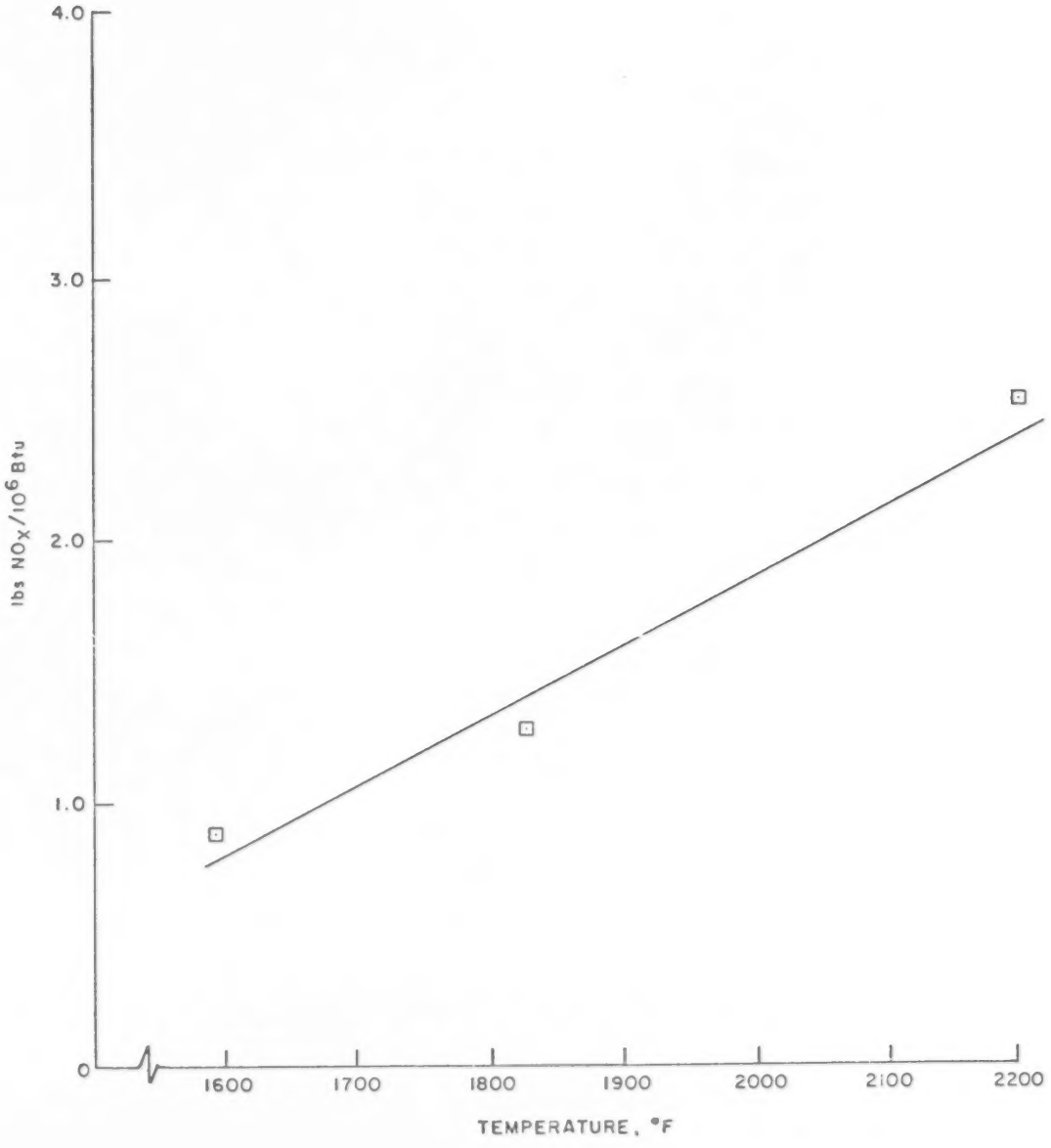

Figure 6-2. Effect of combustion air temperature on NO_x emission factors.

- Titanium and nickel melting furnaces should show the same relationship between NO_x emissions and combustion air preheat as steel furnaces. Nickel and titanium furnaces, however, may be to operated at the higher end of the air preheat range.

- Furnaces buring nitrogen containing fuels (residual fuel oil, N weight percent 0.3) would exhibit predicted NO_x emission factors plus a contribution from fuel bound nitrogen shown in Figure 3-1.

- NO_x emission factors for steel reheat furnaces (0.123 lbs $NO_2/10^6$ Btu),[5] for steel soaking pits (0.113 lbs $NO_2/10^6$ Btu),[5] and for refinery process heaters (0.133 lbs $NO_2/10^6$ Btu)[9] agree with each other and with values predicted by the laboratory studies.

- The values predicted for NO_x emissions from glass melting furnaces at approximately 1500°F combustion air temperatures agree with stack test data under similar conditions (0.788 lbs $NO_2/10^6$ Btu).[5]

- Data for a number of process heaters indicate that burner orientation does not affect NO_x emissions significantly.

DATA EXTRAPOLATION

Although the test programs conducted by IGT provide data on the effects of combustion air preheat on NO_x emissions for the two classifications of heaters, the temperature range studied for the Bloom burner (steel industry furnace) does not extend into the regions of high temperature preheat. Since NO_x emission factors for high temperature preheat are necessary for future modeling activities, data extrapolation is required. The theoretical model of NO_x formation is used as the basis for this extrapolation.

As described in Section 3, the theoretical model predicts that NO_x emissions should increase exponentially with combustion air temperature. In the temperature ranges tested, the experimental data agree well. (These data were represented as linear functions for convenience.) The major limitation of the theoretical model is its inability to account for the increases in residence time caused by backmixing. Since residence time is a simple factor in the integrated form of the differential rate expression, experimental data can be used to develop a simple additive correction factor for the theoretical model to account for increased residence time. The model then can be used to predict NO_x emissions at any air preheat level up to 2000°F for steel (and similar) furnaces.

For the range of temperatures tested, the experimental data show NO_x emissions consistently approximately 0.29 lbs/10^6 Btu greater than that predicted by the theoretical model. Thus, addition of this amount to the theoretical data, shifting the curve upward, produces a model capable of predicting NO_x emissions of high combustion air preheat temperatures and in agreement with experimental data.

The emission factors for steel-type furnaces presented in Table 6-1 result from application of the residence time correction factor and, where appropriate, the fuel type correction factor to the theoretical model. The emission factors for glass melting type furnaces were derived from experimental data only, since the appropriate temperature range is considered.

TABLE 6-1. Emission Factor Summary*

Furnace	Fuel	NO_x Emission Factors (lbs $NO_2/10^6$ Btu) Preheat Temperature (°F)			
		800	1200	1600	2000
Steel Reheat	Coke Oven Gas	0.34	.72	1.40	3.20
	Natural Gas	0.34	0.72	1.40	3.20
Steel Soaking Pit	Coke Oven Gas	0.34	0.72	1.40	3.20
	Natural Gas	0.34	0.72	1.40	3.20
Aluminum Reheat	Residual Fuel Oil	0.64	1.02	1.70	3.50
	Natural Gas	0.34	0.72	1.40	3.20
Aluminum Melting	Residual Fuel Oil	0.64	1.02	1.70	3.50
	Natural Gas	0.34	0.72	1.40	3.20
Steel Forging	Natural Gas	0.34	0.72	1.40	3.20
Annealing	Natural Gas	0.34	0.72	1.40	3.20
Titanium Melting	Natural Gas	0.34	0.72	1.40	3.20
Nickel Melting	Natural Gas	0.34	0.72	1.40	3.20
Cement Kiln	Natural Gas	--	--	0.80	1.80
Glass Melting	Natural Gas	--	--	0.80	1.80
Refinery Process	Natural Gas	0.34	0.72	1.40	3.20

*These emission factors are adequate for use in emission inventory preparation. Application of these factors to specific heaters are subject to the following limitations:

i) The emission factors are based on experimental data only from two types of industrial furnaces, and they are suggested for application to other industrial furnaces based on similarities in furnace design and operating conditions.

ii) Except for the glass melting furnace and cement kiln, the emission factors for 1600 and 2,000°F air preheat temperatures are extrapolated values.

iii) For residual fuel oil, the listed NO_x emission factors are for 0.3 weight percent N content and 19,600 Btu/lb heating value, assuming 100 percent conversion of fuel N to NO.

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